SPACE SIMULATION CHAMBER INSTRUMENTATION

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Aerospace Environmental Facility
ARO, Inc.

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FOREWORD

A summary of this report was presented at the AGARD Session on "Space Simulation Chambers and Techniques" in Rome, Italy, on October 22-25, 1962.

ABSTRACT

The measurement of chamber and test vehicle parameters in large space environmental chambers has become a new technology in the field of instrumentation. Modification of old established techniques and the development of new techniques for the purpose of measurement of multichannel parameters associated with space chamber testing has become of utmost importance in recent years. This paper contains a comprehensive state-of-the-art examination in the field of space environmental chamber instrumentation.

PUBLICATION REVIEW

This report has been reviewed and publication is approved.

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1.0 INTRODUCTION

With the introduction of large chambers for space environmental testing, the instrumentation of these chambers has become of utmost importance. In smaller chambers, where limited numbers of parameters were measured, laboratory techniques could be employed. In large chambers, where vehicles up to full-scale are tested, many hundreds of channels of data must be processed and evaluated at high speeds. Old techniques are being applied and modified where necessary, but, in general, a new technology in instrumentation is being developed for these chambers. It is the purpose of this paper to review the state-of-the-art of the instrumentation in the fields of vacuum measurements, cryogenic temperature measurements, thermal radiation measurements, and test vehicle instrumentation.

2.0 VACUUM MEASUREMENTS

Since, at present, the total pressure is commonly used as the determination of the simulated altitude in the space chamber, it is important that chamber instrumentation include provisions for performing accurate pressure measurements. This is not a trivial requirement because all commercially available pressure measuring devices that are usable over the primary range of interest from 10^{-3} to 10^{-9} torr are sensitive to the gas composition. The chamber gas composition will, in general, be unknown, particularly at the lower pressures. Therefore, determination of the residual gas composition becomes important in the accurate determination of the chamber pressure.

2.1 PRESSURE AND VACUUM GAGES

A summary of commercially available vacuum-measuring devices which are available and useful in space chamber instrumentation is presented in Fig. 1. This list excludes a large number of gage designs which are not commercially available and many of which are only of academic interest. It also excludes the McLeod gage which is considered the "primary" standard in the 10^{-1}- to 10^{-5}-torr range, but is not generally applicable for use in space chambers. For their operation, the first three types presented depend on the displacement of a

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liquid or mercury column or upon the mechanical deformation of a bellows or a thin wall. These devices indicate absolute pressure or may easily be calibrated to do so. Little difficulty is encountered in the application of these types, and they are mentioned only for completeness.

The vacuum gages presented as types 4 through 9 (Fig. 1) are all sensitive to gas type as well as density. In addition, many of these gages have other peculiarities which must be understood for successful application. None of these gages is an absolute pressure-measuring device, and all must be calibrated, with a specific gas, against absolute pressure-measuring devices, such as one of the first three types and/or the McLeod gage.

2.1.1 Thermal Conductivity Gages

Heat-conductivity gages, such as thermocouple and Pirani (types 4 and 5, Fig. 1), have poor resolution in the 760- to 5-torr range as compared to their resolution in the 5- to 10^{-3}-torr range. This poor resolution is caused by the fact that the heat conductivity for a particular gas varies only slightly in the 750- to 5-torr range but decreases linearly with pressure from a few torr down to a few microns pressure (Ref. 1). Since the coefficient of heat conductivity is different for various gases, it is apparent that the calibrations of heat-conductivity gages are affected by gas composition. These calibrations will also be affected by large changes in the ambient temperature.

2.1.1.1 Thermocouple Gages

Thermocouple gages (type 4, Fig. 1) are the simplest of the electrical vacuum gages. A simplified schematic of such a device (Ref. 1) is presented in Fig. 2 along with a typical calibration. In order to maintain a constant current through the filament as the resistance of the filament changes, the resistance of the current-adjust rheostat is made large compared to the resistance of the filament. Normal filament currents are on the order of 100 ma, and the filament operates at a temperature varying from 100 to 200°C. The filament temperature varies with the amount of heat conducted away by the system gases. Consequently, the filament temperature, which is monitored by the thermocouple, becomes a function of the system pressure.

2.1.1.2 Pirani Gages

A simplified schematic of a Pirani gage is shown in Fig. 3 (Ref. 1) along with a typical calibration. The compensator filament is sealed in a highly evacuated bulb, whereas the other filament is exposed to the pressure to be measured. A constant voltage is applied to the wheatstone bridge, and the rheostat is adjusted to give zero meter reading at low system pressure on the order of a few tenths of a micron. As the system pressure increases, more heat is conducted away from the manometer filament, and its resistance changes. Consequently, the bridge becomes unbalanced, as monitored by the milliammeter whose reading becomes a function of the system pressure.

2.1.2 Ionization Gages

The remaining vacuum-measuring devices listed in Fig. 1, types 6-10, are all types of ionization gages. However, even though they are of the same general type, they differ considerably in their principles of operation.

2.1.2.1 Alphatron Gages

The Alphatron, developed by Downing and Mellen of NRC Equipment Corporation, indicates pressure by measuring the current of positive ions created by alpha particles in an ionization chamber. Figure 4 (Ref. 1) shows a diagram of the Model 530 Alphatron along with the relative response to different gases. Two ionization chambers are provided to give a linear response for air from 10^{-4} to 10^{3} torr. The chambers are maintained at positive 108 v with respect to the collectors. The large chamber, used in the range from 10^{-4} to 10 torr, has a volume of 51 cc, and the radium source emits alpha particles at the rate of 100 microcuries to give a gage sensitivity for air of about 10^{-10} amp/torr. The small chamber is used in the 10- to 10^{3}-torr range. It has a volume of 0.2 cc, a radium source of 1.5 microcuries, and a sensitivity for air of about 1.5×10^{-13} amp/torr. The radium sources are sealed to prevent the loss of radon gas so that the succeeding decay products may be held in the source and their alpha activity utilized (Ref. 1).

Few problems are encountered in the successful application of alphatrons provided care is taken to avoid contamination of the ionization chambers and due attention is paid to their relative response to different gases.

2.1.2.2 Cold-Cathode Discharge Gages

Another type of ionization gage which is generally employed in space chamber instrumentation is the cold-cathode discharge gage. The most familiar of this type is the Phillips gage, which is presented in Fig. 5 along with its relative response to different gases. The two cathode discs are constructed of a slightly radioactive material, such as zirconium or thorium, to help strike the discharge. In operation, secondary electrons are produced at the cathode surfaces by bombardment with positive ions which obtain energy during acceleration to the cathode. The weak magnetic field exerts little influence on the motion of the positive ions, and when one is created it is accelerated directly to the cathode. The paths of the secondary electrons, however, are greatly influenced by the magnetic field, and the electrons travel long helical paths before reaching the anode. Consequently, the number of ions produced per electron in reaching the anode is greatly enhanced by the presence of the magnetic field. The discharge current is a function of the gas composition and density, and, therefore, may be calibrated in terms of system pressure with a specified gas composition.

P. A. Redhead of the National Research Council of Canada designed a cold-cathode ionization gage (type 9, Fig. 1) which is usable to a much lower pressure than the Phillips gage. The Redhead gage is similar to the Phillips gage both in construction and in principle of operation, but it has several basic improvements over the Phillips gage. The discharge current in the Redhead gage is a linear function of the pressure. This is a very desirable feature when considering the present state-of-the-art of gage calibration in the high- and ultra-high vacuum range. The Redhead gage uses a higher anode voltage (6000 v), a higher magnetic field (1000 gauss), and realizes a higher sensitivity (4.5 amp/torr) than the Phillips gage. The discharge current of the Redhead gage is amplified by an electrometer amplifier capable of detecting currents down to approximately 10^{-13} amp. Therefore, the gage may be used to read pressures down to about 2×10^{-14} torr.

Cold-cathode discharge gages are generally rugged, dependable devices, but they do have some limitations which should be mentioned. It has been found that continuous operation of the Redhead gage in the 10^{-6}- to 10^{-4}-torr range is not recommended because to do so will destroy the gage sensitivity. This apparently is caused by cathodic sputtering at these higher pressures. Another cold-cathode gage characteristic which may be important in certain cases is that these gages normally have large pumping speeds compared to hot-cathode ionization gages. When gages have large pumping speeds, care should be taken to maintain sufficient conductance between the gage and the vacuum system. The pressure drop (ΔP) across the tubulation between the gage and the system is given by

$$\frac{\Delta P}{P} = \frac{S}{C}$$

where S is the gage pumping speed and C the tubulation conductance (Ref. 2). The Redhead gage has a pumping speed of one liter (ℓ) per second; to keep the error caused by gage pumping less than 5 percent, C should be about 20 ℓ/sec. Therefore, the gage tubulation should be about 2 in. long and 1 in. in diameter.

2.1.2.3 Hot-Cathode Ionization Gages

In the family of ionization gages, the hot-cathode, inverted-triode ionization gage is the most commonly used in space chamber instrumentation. Figure 6 shows a simplified schematic of this gage along with its relative sensitivities. The positive ion collector is maintained a few volts negative with respect to the filament. This is necessary because the electrons are expelled from the filament with about 5 ev energy and, in the absence of collector voltage (E_c), would reach the collector. In operation, thermionic electrons from the filament are accelerated through the grid structure. They oscillate in and out of the grid structure until they finally collect on the grid. Positive ions are created by electron bombardment inside the grid structure and are accelerated to the collector. Under normal operating voltages and at pressures less than 10^{-4} torr, the glass walls float at a slightly negative potential. The gage operates on the principle that the collector current is proportional to the product of the grid current and system pressure (Ref. 3). The constant of proportionality is the gage sensitivity,

$$S = \frac{(I_c/I_g)}{P}$$

where I_c is the collector current and I_g is the grid current. A typical value of S for commercial gages is 10 torr^{-1}.

The triode ion gage has been the object of a great deal of experimental investigation dating back to 1916 (Ref. 1). Previous to about 1950, the gage took the conventional form, structurally resembling a triode vacuum tube with the filament located along the centerline of the grid. The ion collector was a cylinder which contained the filament and grid structures. This type is still used and gives good results to about 10^{-8} torr. The VG-1A gage shown in Fig. 9a is of this general design.

The conventional design was a source of considerable confusion for several years because, regardless of the integrity of the vacuum system, the gage never indicated a pressure less than about 10^{-8} torr. Nottingham first suggested (Ref. 4) that this was caused by the existence of a residual collector current which was independent of the pressure. This current was found to be produced by the impingement of soft X-rays upon the collector and the resulting ejection of photoelectrons from the collector. The X-rays were found to be created at the grid by bombardment of the grid with the electrons that constitute the normal grid current (Ref. 3). Consideration of this problem led Bayard and Alpert in

1950 to develop the inverted triode ion gage of the general type shown in Figs. 9b and c. A comparison of the collector current characteristics of the inverted and conventional ionization gages is shown in Fig. 7 (Ref. 3). These curves illustrate the existence of the X-ray-induced collector current at the lowest pressures, with the X-ray current increasing with grid potential. The curves of the higher pressures are normal in that they are similar to curves obtained for gas ionization probability by electron impact. Figure 7b illustrates that, even with the thin wire collector, X-ray currents again reach limiting proportions in the Bayard-Alpert gage at pressures in the 10^{-11}-torr range.

Figure 8 presents some Bayard-Alpert tube characteristics for a normally operating tube. Note in Fig. 8b that if E_c were reduced further toward zero, I_c would suddenly go negative.

In spite of the large amount of developmental work to which it has been subjected, the hot-cathode ionization gage is subject to several sources of error, most of which are not well defined and are uncontrollable. In addition to being gas composition sensitive, as shown in Fig. 6, the gage can pump system gases. Two modes of pumping exist (Ref. 2). The first mode is electronic pumping, which results from the acceleration of ions created outside the grid to the filament and glass wall which are maintained negative with respect to the grid. As a result of this, the glass walls can attain large positive potentials on the order of +30 to +40 v with respect to the filament when the pressure is in the 10^{-4}-torr range. The large potential materially affects the electron ballistics in the tube and helps reduce the gage sensitivity in the 10^{-4}-torr range. In addition, sudden drops in the apparent gage sensitivity are commonly seen in the 10^{-4}-torr range with commercial glass tubulated gages. These changes may be attributed to Barkhausen-Kurtz oscillations in the gage (Ref. 2).

The second mode of gage pumping is by chemical pumping which results from chemisorption of gases on the gage electrodes and evaporated films on the glass bulb. The rate of chemical pumping varies with the type of gas. Total gage pumping speeds for N_2 are commonly on the order of 0.2 to 2 ℓ/sec with gages running at 10 ma emission (Ref. 2). Pumping speeds for other gases, such as CO and H_2, may be much higher and on the order of 5 to 10 ℓ/sec (Refs. 4 and 5).

In addition to pumping, the hot-cathode ionization gage has a number of other peculiarities which should be noted. Chemical reactions at the hot filament are capable of materially altering the character of the residual gas, particularly if the gas contains a high percentage of H_2O, H_2, or hydrocarbons (Ref. 2). Another peculiarity which has been observed is the Blears effect which involves errors in glass tubulated gage readings when the system gases are composed of a high percentage of residual oil vapors (Ref. 6). Under these conditions, nude-mounted gages have been observed to indicate pressures higher by factors of ten than glass tubulated gages mounted on the same system.

Some of the peculiarities of the glass tubulated gage can be avoided through the use of nude-mounted gages of the type shown in Fig. 9c. Nude gages may be mounted on metal flanges with the gage elements projecting into the chamber. This arrangement decreases or eliminates errors caused by the Blears effect, changing wall potentials, Barkhausen-Kurtz oscillations, and gage pumping. However, it appears that nude-mounted gages are much more susceptible to contamination than tubulated gages, particularly in oil-diffusion-pumped systems, and require calibration more frequently than tubulated gages.

Another problem which arises in conjunction with the application of ionization gages in space chambers is how to obtain a representative reading of the pressure to which the vehicle in the chamber is actually exposed. If the chamber contains a cryogenic liner, part of the condensables originating at the vehicle will be removed at the liner. Therefore, gages located at the vehicle and optically exposed to the cold wall will read differently from gages located at the wall and optically exposed to the vehicle. Holkboer and Santeler have investigated (Ref. 7) this problem and have conceived the principle of a space simulator gage which is mounted on the chamber wall and yields readings from which may be deduced the actual pressure to which the vehicle is exposed. The space simulator gage is basically a nude-mounting Bayard-Alpert gage mounted in a metal container. Portions of the container are cryogenically cooled, thus reducing by a specified factor the sensitivity of the gage to cryogenically pumped gases (Ref. 7). This gage is under development by General Electric Company (GE).

2.2 MASS SPECTROMETRY

The fact that ion gages are gas composition sensitive precludes their possible use as a very accurate pressure-measuring device in an undefined atmosphere. This suggests the use of mass spectrometry equipment in space chambers for residual gas analysis where accurate pressure measurements are required. Residual gas analyzers on the chamber are also useful for checking the performance of the various systems in the chamber. They help identify limiting gas loads which may originate from atmospheric leaks, cold leaks in cryogenic panels, vehicle outgassing, or leaks in hydraulic systems in the chamber.

Several commercial, residual gas analyzers are available. A summary of these devices is presented in Fig. 10. A simplified diagram of a representative type of a magnetic-sector mass spectrometer is shown in Fig. 11. This device has a Nier ion source in which electrons from a hot filament are focused by a magnet and traverse an enclosed ionizing region. Ions created in the region are drawn out through a slit by the electric field created by grid shapes J_1-J_2 and J_3. The potentials of J_1 and J_2 differ slightly and serve to center the ion beam on the grounded exit aperture. The ions are created in a region of high potential, V, and emerge through the grounded exit aperture with velocity v and energy eV when singly ionized. If the mass of a particular ion is M, then the kinetic energy at the exit aperture is

$$\frac{1}{2} Mv^2 = eV$$

$$v = \sqrt{\frac{2eV}{M}}$$

While passing through the magnetic separation section, the centripetal force equals the magnetic field force:

$$\frac{Mv^2}{R} = evB$$

where R is the radius of curvature of the ion beam path and B is the value of the magnetic field applied to ion separation region. Substituting the previous expression for v into this gives:

$$M = \frac{eB^2R^2}{2V}$$

Therefore,

$$MV = K$$

where K is a constant for the mass spectrometer. A desired portion of the mass spectrum is then scanned by smoothly varying the accelerating potential, V.

Several modifications of the above simplified example are commonly employed in commercial analyzers. Among these are modifications of the ion source to allow omitting the electron beam focusing magnet. Also, electron multipliers are commonly substituted for the ion collector to realize higher sensitivity and faster mass scan rates. It will be noticed that it is possible to scan the mass spectrum by smoothly varying the magnetic field at a constant accelerating voltage. Residual gas analyzers with this feature are available which give adjacent mass resolution to about 130 atomic mass units (A. M. U.).

Another more expensive, but highly versatile, mass spectrometer which is applicable to space chamber instrumentation is the time-of-flight type. A block diagram of this type is presented in Fig. 12. For mounting on a large vacuum chamber, the ion source is modified and denuded to project directly into the chamber. The ion drift tube and its associated ion pump projects outside the chamber. The drift tube and chamber are separated by a pressure baffle whose conductance may be designed as low as 0.6 ℓ/sec. The analyzer operates in a pulsed mode at a repetition rate of 10 kc. Thus, a mass spectrum is generated each 100 microseconds (μsec). At the start of each cycle, a beam of electrons is pulsed through the ion source region for about 0.5 μsec and creates ions in the region (Fig. 12). As soon as the electron beam is shut off, the ions are pulsed out of the ionizing region and are accelerated to 2800 eV energy by the potential on the drift tube liner. Mass separation occurs as the ions traverse the ion drift region. When the ions enter the ion drift region, they are in closely bunched packets, with a packet entering each 100 μsec. As a packet traverses the drift region, the lower mass-to-charge ratio (m/e) particles speed ahead, and the higher m/e particles arrive at the detector at a later time. The detector is an electron multiplier of the crossed electric-magnetic field type in which the electron paths are cycloids. Stable gains in excess of 10^8 can be obtained from the multipliter (Ref. 8). The electron multiplier puts out an amplified packet of electrons corresponding to each ion species collected at the input of the multiplier. The output packet of electrons is collected on one of seven possible output anodes. The particular anode on which the packet is collected depends on which is pulsed at the proper time to intercept the packet (Fig. 12). The time at which six of the anodes are pulsed is manually adjustable, and of these, one has an automatic time-scanning mode of operation to allow mass spectrum scanning. All electron packets not intercepted by the first six anodes are collected on the seventh anode (not shown in Fig. 12) and displayed on a fast, triggered oscilloscope. This over-all arrangement makes it possible to continuously monitor the concentration of five gases and simultaneously obtain a chart and/or an oscillographic recording of any desired portion of the mass spectrum from 2 to 800 A. M. U. Among the variables in the design of an instrument are the number of output channels, the scan time, and the drift tube length which determines the resolution. Ten or more output channels can be provided. Scan times can be as short as 10 μsec, even though this complicates the spectra because of overlapping of the high mass range with the low mass range of the successive scan. Resolution of the time-of-flight mass spectrometer can be made as high as 300, with 204 being a standard value.

Regardless of the type of mass spectrometer used for partial pressure measurements, the following three assumptions are made (Ref. 9):

1. Each molecular species gives a constant mass spectrum, or cracking pattern, that is characteristic of the molecule. Figure 13 presents some typical cracking patterns.

2. The mass spectra of different components in a mixture are linearly additive.

3. The absolute intensities of the ion beams (peak heights) given by any component are proportional to that component's partial pressure in the ion source.

Concerning the first assumption, the exact nature of the cracking pattern depends primarily on the energy of the ionizing electrons, but, also, it varies somewhat with the degree of cleanliness of the spectrometer tube and with aging of the filament. Periodic checks of cracking patterns with pure gases are necessary. The second and third assumptions are not strictly correct, as it has been demonstrated that when the mass spectrum of a given gas in the ion source is observed and at the same time a second gas is introduced, the spectrum of the first gas can change. This interference effect is not well understood (Ref. 9), and in exact analytical work, mass spectrometer operating conditions must be determined which minimize the effect. However, for the purpose of partial pressure measurement in space chambers, all of the three assumptions above are taken to be correct.

2.3 CALIBRATION

One of the most serious problems in vacuum instrumentation is the lack of universally accepted standards against which to calibrate pressure and partial pressure-measuring devices below 10^{-3} torr. A great deal of study and developmental activity has been directed toward the solution of this problem, and several techniques have been developed. The problem is still not well resolved, however, and the Bureau of Standards will not certify gages below 1 torr.

2.3.1 McLeod Gage

The McLeod gage is the most widely used "standard" below 10^{-3} torr. This gage, an application of Boyle's Law, traps a measured volume of low-density gas and compresses it with a mercury piston into a closed capillary tube. The gage is designed so that the pressure and volume of the compressed sample may be determined by measuring the height of the mercury column in the closed capillary tube. With the original volume known, the pressure at which the sample was trapped can be calculated.

The McLeod gage is usable down to about 10^{-5} torr, and at this pressure its accuracy is approximately ±10 percent. It is possible to construct McLeod gages capable of measuring pressures down to about 10^{-7} torr, but the McLeod gage is subject to several sources of error which limit its usefulness to about 10^{-5} torr. The most significant source of error is gage contamination with condensable vapors. The gage is constructed of glass which must be thoroughly outgassed with a soft flame, and the mercury used must be cleaned frequently by vacuum distillation. The gage must be cold trapped to keep mercury out of the vacuum system and to keep condensable vapors out of the gage.

The McLeod gage is not a direct-reading instrument, and all things considered, the utility of this gage is severely limited. Although it is widely used for determining ion gage sensitivities, it is not generally useful for determining mass spectrometer sensitivies because most mass spectrometers do not operate well above about 10^{-5} torr.

2.3.2 Calibrated Conductance Techniques

Calibrated conductance techniques have been employed since 1928 (Ref. 6) to create accurate low pressures against which to calibrate instruments. These techniques have been used successfully from 10^{-4} to 10^{-8} torr by several workers (Refs. 10 and 11) who predict that such techniques are extendable to even lower pressures, depending on the ability to attain ultra-high vacua in the calibration system. The basic elements of one type of such a dynamic calibration system is shown in Fig. 14 (Ref. 10). The orifice C_2 is a circular orifice in a thin metal diaphragm separating the test dome and high vacuum chamber. The conductance of C_2 is on the order of 100 ℓ/sec, depending on the particular design of the system. The conductance C_1 is of the form of a porous plug of very low conductance. Ideally, C_1 is a conductance of approximately 10^{-5} ℓ/sec with pore diameters sufficiently small that molecular flow through the plug exists up to atmospheric pressures. Owens (Ref. 10) has investigated materials usable in this capacity, and the most promising appears to be fritted glass or porous Vycor glass.

The performance of the system shown in Fig. 14 can be analyzed by equating the flow through C_1 to the flow through C_2 at equilibrium.

$$C_1 (P_1 - P_2) = C_2 (P_2 - P_3)$$

Since $P_1 \gg P_2$, this reduces to

$$C_1 P_1 = C_2 P_2 (1 - P_3/P_2)$$

Therefore,

$$P_2 = \frac{(C_1/C_2) P_1}{(1 - P_3/P_2)}$$

The pumping speed of the diffusion pump is designed large compared to C_2 so that the term P_3/P_2 is small compared to unity. Ideally, P_3/P_2

is on the order of 0.01 and may be neglected. This last expression will then be recognized as $P_2 = KP_1$ where K is a constant of magnitude of about 10^{-6}. Then a range of P_1 from 10μ to 100 torr would create a P_2 ranging from 10^{-8} to 10^{-4} torr.

The orifice flow technique can be used to create standard pressures up to where the mean-free path becomes comparable to the diameter of the orifice C_2 (Ref. 11). The lower usable pressure limit depends on the magnitude of the ultimate pressure attainable in the test dome. For example, only one percent error would be contributed by the background to a calibration at 1×10^{-8} torr provided the system had first been pumped down to a base pressure of 1×10^{-10} torr. At higher pressures this error would be even less, and the error in P_2 would be determined by the accuracy of measurement of K and P_1 (Fig. 14).

The orifice flow technique, used in conjunction with porous plugs to accurately create the small flows required, has several desirable features. Dynamic conditions exist in the test dome, and sorption effects become negligible. A large number of gases and vapors can be used as the calibrating gas (Ref. 6). The constant K is theoretically independent of the molecular weight, and it is not necessary to determine its value except for one molecular species. Another advantage of the calibrated-orifice-porous-plug technique is that parallel inputs to the test dome (Fig. 14) may be employed. Then the equation for P_2 may be applied to each input, and mixtures of accurately known partial pressures may be created. This approach affords the possibility of evaluating mass spectrometer performance with accurately known and easily changed mixtures of gases.

Of the various techniques applicable to the determination of ionization gage and mass spectrometer sensitivities, the orifice flow technique used in conjunction with porous plugs to create the small flows required appears to be the most promising at the present time.

2.3.3 Multiple Expansion and Rate-of-Rise Techniques

Several other gage calibration techniques have also been developed. Among these is the multiple expansion method in which a small quantity of gas of accurately known volume and pressure is expanded into a large vessel initially at "zero" pressure. A small sample at the resulting pressure may be trapped and the process repeated. Such repeated applications of Boyle's law have been used to create "standard" pressure down to about 10^{-6} torr. The technique is subject to several obvious sources of error, the most prominent of which are sorption and desorption effects occurring at the chamber walls and in gages being calibrated.

Another technique which may be employed to calibrate gages or to determine mass spectrometer sensitivities is the rate-of-rise technique. This technique is presently being used at Arnold Center to determine mass spectrometer sensitivities at total pressures in the 10^{-6}-torr range (Ref. 13). In this technique the mass spectrometer is installed on a vacuum system which has a volume of several hundred liters. The system is baked and exhausted to a very low pressure on the order of 10^{-8} torr after which the system is cooled and briefly purged to 10^{-6} torr with the desired pure calibrating gas. The system is then pumped back down near 10^{-8} torr, and the vacuum pump is valved off. The calibrating gas is then introduced through a calibrated leak for a measured length of time. With the volume of the system known, the resulting pressure rise at any time can be easily calculated. When the pressure rise becomes large compared to the base pressure, the resulting mass spectrometer response to the parent peak is noted, and a sensitivity factor is calculated in terms of peak height units of deflection per unit pressure at specified mass spectrometer operating conditions. This sensitivity factor is then assumed to remain constant over the operating pressure range of the mass spectrometer. This technique has yielded sensitivity values which are repeatable to about two percent. The primary disadvantages of this technique are that it is somewhat time consuming and that, in practice, the standard leaks normally used must be calibrated with each molecular species used.

3.0 THERMAL RADIATION MEASUREMENTS

In chambers equipped with solar simulation and/or albedo and earth radiation simulation systems, it is necessary that instrumentation be provided for the measurement of the radiation parameters. Measurements must be made to determine the spectral distribution, total intensity, and collimation across the field of view of the energy irradiated on the test rhombus. The methods of measurements and their functions will be discussed.

For solar simulation in earth orbit, the carbon arc lamp and the mercury-xenon arc lamp are the two types used in the present family of space chambers. The advantages and disadvantages of each will not be discussed here, but some variation of methods of measurement exists between the two. The spectral distribution of radiation is of utmost importance because of the varying or unknown emissivity of the test article, and collimation should be closely reproduced when solar cells and unsymmetrical vehicle shapes are being tested. For these reasons, the solar beam is monitored for spectral distribution, uniformity of total intensity, and collimation to ensure that proper simulation is being attained.

In chambers now in operation, the albedo and earth radiation simulation is accomplished with tungsten filament heaters; no attempt is being made to reproduce the spectral energy content or to collimate the beam. Therefore, the albedo and earth radiation measurements can be made with total radiation detectors that are capable of measuring total intensity radiation from approximately 1 to 100 w/ft^2.

3.1 SPECTRAL DISTRIBUTION

About 95 percent of the total radiation energy in a solar simulator falls in the 0.2- to 2.0-micron band. Basically, two methods of measuring the spectral distribution of solar simulator radiant energy are now used. One of these is the use of a spectrophotometer which incorporates a monochromator, a detector, and an optical system for collection of the radiant energy. The other method is the use of a total radiation detector, such as a thermopile radiometer, with the introduction of various optical filters for selecting specific bandwidths of energy.

Commercially available spectrophotometers have to be modified so that they can adequately collect the solar radiation and the output of a calibration source. Also, it may be necessary to modify the detection and readout systems for accomplishing faster scans. The basic spectrophotometer consists of an optics system for radiation collection, a monochromator for spectral selection, and a detector for intensity measurements. Most commercial models come equipped with a readout device, such as an x-y recorder. When an x-y recorder is used, the output of the detector in the spectrophotometer is applied to one axis of the plotter, and the input to the other axis is taken from the output of a slide wire that is attached to the monochromator wavelength drive system. A plot of radiation intensity versus wavelength is obtained with this technique.

For spectral distribution calibration, the spectrophotometer must be checked against a standard tungsten lamp that has been calibrated against a primary standard by the National Bureau of Standards. This calibration can be a tedious task, and optics for quickly switching inputs from the standard lamp to the unknown radiation source should be provided in the spectral measurement system.

The second calibration method is accomplished by using a total intensity blackbody radiometer as a sensor and introducing fixed optical filters for limiting measurements to specific bandwidths. Interference filters and interference wedge filters will cover the spectral band of interest. Absorption filters could be used but have the disadvantage of having wide bandwidths and being more temperature sensitive than interference filters. The radiometer and filter calibration technique is not as accurate as using a spectrometer, but it has the advantage of being smaller and more convenient for in-chamber calibrations.

3.2 TOTAL INTENSITY

The mean zero, air mass solar constant in earth orbit is approximately 130 w/ft^2. The total integrated beam intensity is important to all tests performed in a space simulation chamber. A variation in beam intensity will obviously affect the thermal equilibrium of a vehicle, the output of solar cells, and can accelerate or decelerate the aging of materials.

The total intensity measurements from a solar simulator could be obtained from integrating the spectrum at each point; however, the blackbody characteristics of a radiometer absorbs all energy in the wavelengths of interest in the solar spectrum. The radiometer has a blackened-copper disc as a sensing surface with a 180-deg or less field of view. It is a thermopile detector with a series of thermocouples mounted between the backside of the sensing disc and a reference junction heat sink. All surfaces other than the sensing surface of the radiometer are shielded from sources of direct radiation by highly reflective surfaces so that only the blackened disc receives the radiant solar energy. The output of the radiometer is a measure of the differential temperature between the sensing surface and the reference junction heat sink. The reference junction is usually cooled with a liquid coolant, such as liquid nitrogen or water, so that a constant temperature is maintained. The number of thermocouples determines the sensitivity and also affects the controlled heat loss of conduction when used in a vacuum. Increasing the heat loss of conduction improves linearity but decreases sensitivity; therefore, a design compromise is usually in order for optimum linearity and sensitivity.

The thermopile detector (radiometer), as shown in Fig. 15, is the most commonly used total intensity detector. It is calibrated against a standard tungsten lamp, and some manufacturers furnish calibrated radiometers that have compensating circuitry when the radiometer is used in a vacuum.

3.3 COLLIMATION

As mentioned previously, the degree of collimation is important where the testing of vehicles with irregular shapes or with solar cells is being conducted. The radiation from the sun subtends an angle of about 32 minutes of arc at the earth's orbit, but most solar simulators are specified to only about ±1.5 deg of arc.

There are no instruments available for the direct measurement of decollimation, but two techniques have been used. One of these methods is shown in Fig. 16a: a parabolic mirror of known focal length intercepts the beam and the image size is measured with a small thermopile by sweeping slowly across the diameter. The decollimation, θ, is determined as

$$\theta = \tan^{-1} \frac{\text{image radius}}{\text{mirror focal length}}$$

The image diameter is determined by finding the 10 percent magnitude points of the intensity curve with the thermopile. This method is presently being used in the development of carbon arc solar simulation modules by RCA for the Arnold Center Aerospace Systems Environmental Chamber, Mark I.

Another method for collimation measurements is with the use of a long, blackened, narrow tube where the diameter of the tube divided by the length is very small. As seen in Fig. 16b, the beam is allowed to enter the open end of the tube while a detector is placed at the other end. If the tube is rotated about the detector end, the detector output will fall to zero when the beam fails to pass through the rod. The decollimation angle, θ, is the angle made by the tube when the detector goes from maximum to zero.

3.4 UNIFORMITY

The uniformity of the solar beam above the atmosphere of the earth is homogeneous; therefore, it would be desirable if the simulated solar beam were homogeneous. In practice, perfect uniformity cannot be achieved because of the necessity of using an optical system. However, uniformity is important and should be simulated to about ±5 percent for thermal balance testing, but it becomes less important in a rotating vehicle. For solar cell testing, better uniformity should be achieved, but for large simulator systems, ±5 percent is normally acceptable.

Uniformity measurements are generally made with a radiometer, as discussed in section 3.2, by sweeping the sensor across the beam.

For high-speed measurements of solar banks, a type of photo-detector or solar cell may be used for relative measurements. With the photo-detector technique a large bank of solar sources can be scanned for "hot or cold spots" caused by overlap or underlap of beams of adjacent solar modules.

3.5 CALIBRATION PROCEDURES

It is usually necessary for two calibration procedures to be established for a solar simulation system. The first is the calibration of individual solar modules with their associated optical systems, and the second is the calibration of the entire solar simulation assembly when all modules are integrated into the space chamber (Ref. 15).

Calibration of the individual modules before installation in the chamber must be done with precision equipment. At this time, spectral distribution, collimation, and uniformity are accurately determined, and final adjustments and alignment of module components are made. Fixed laboratory equipment, such as a spectrophotometer, can be used along with other optical accessory instruments previously mentioned. A typical calibration system that is proposed for the calibration of carbon arc solar modules at Arnold Center is shown in Fig. 17.

The in-chamber calibration of the fully integrated solar simulation system is more difficult because all instrumentation must be adapted for use in the space chamber. For fast uniformity measurements, a thermopile radiometer equipped with a filter wheel measures both total intensity and spectral distribution when scanned across the solar field. The geometry of the space chamber and the size of the irradiated test rhombus dictates the mechanical equipment required to scan the solar field. For rapid uniformity checks of total intensity in order to determine deviations in intensity, a photo-sensitive detector can be rapidly scanned across the field. This will allow observation of intensity deviations as the output of the photo-detector is displayed on an oscilloscope or other fast-recording instruments.

4.0 CRYOGENIC THERMOMETRY

The measurement of cryogenic temperatures in space environmental chambers is necessary for monitoring the performance of cryogenic pumping systems. Surface temperatures of cryogenic panels and in-line temperatures of cryogenic coolants are the basic measurements required. The temperatures monitored fall into two basic bands: (1) 60 to 150°K and (2) 10 to 30°K, which correspond to liquid nitrogen, gaseous helium, and liquid hydrogen temperatures. Accuracies of ±1°K within the specified bands mentioned above should be realized. In order to observe the panel temperatures during cool-down or warm-up of the chamber, the temperature should be monitored from ambient down to its normal operating temperature with an accuracy of ±5°K.

4.1 BASIC REQUIREMENTS

The basic requirements of a temperature-measuring system for cryogenic refrigerants and their associated panels are presented with a discussion of the peculiarities, advantages, and limitations associated with each.

1. Large numbers of measurements must be made to adequately determine the condition of a cryogenic system. Several hundred measurements are not uncommon in large space environmental chambers.
2. The system must operate for long periods without interruption; therefore, stability and calibration checks can be made on the system while in operation.
3. Over-limit conditions must be set so that panel or other cryogenic system failures can be avoided.
4. All sensors must be interchangeable in order to reduce the complexity and cost of the data-gathering system. Like sensors should have the same sensitivity, scale factor, and linearity so that the data-gathering system can have one common input.
5. The sensors should be rugged, easily installed, operate into long cables, unaffected by pressure variations, and require no or infrequent calibration.

4.2 SENSORS

The cryogenic thermometer or sensor has graduated from the laboratory to multi-application use in the past few years. However, each sensor must be examined according to its individual characteristics before deciding on its specific application.

4.2.1 Metallic Resistance Thermometers

Because the electrical resistance of metals increases with an increase in temperature, commonly referred to as a positive coefficient of temperature, some pure metals and alloys have sufficient sensitivity (increment change of resistance per increment change of temperature) and repeatability to be used as a thermometer. Platinum, nickel, and copper are the most commonly used metals, but platinum is the only one sensitive and stable enough for extensive use in the cryogenic region. Copper has such a low basic resistivity that a sensing bulb suitable for the cryogenic region would be too large and bulky because of the amount of wire required to have a desirable resistance value. Lead has good cryogenic thermal characteristics but is not used because it will flow at room temperature, causing a change in calibration. Indium could be used, but it is too soft to be drawn into fine wires.

Platinum wire of the highest purity (0.001- to 0.025-in.-diam) mounted as nearly as possible strain-free, annealed, and protected against contamination is the most widely used precision thermometer (Fig. 19a). This type is used by National Bureau of Standards as their calibration standard from 11 to 90°K and the standard for interpolation of the International Temperature Scale from -182 to 630°C. Platinum wire is available in a highly pure and reproducible state, can be easily worked, is relatively immune to corrosion, and has a relatively simple resistance-temperature relationship (Fig. 19b). These precision thermometers are very fragile, rather large and bulky, and expensive; therefore, they are not extensively used for environmental test chamber measurements.

There are many other versions of sensors using platinum being manufactured that are more rugged and suitable for chamber installations, especially for in-line measurements, that still retain many of the precision features of a standard. Even for surface measurements there are some which are supposedly mounted in a strain-free manner and still have very rugged characteristics.

Platinum can be fused in glass, quartz, or pyrex rods or tubes or imbedded in alumina, but then it is no longer strain free. Although the precision decreases, this form may be more suitable for some applications, especially since the cost is much less. With the platinum embedded in an insulator, such as alumina, and enclosed in a metal case, a very rugged and fairly easy to mount thermometer exists. However, with any sensor made from pure or nearly pure metal, the resistance will be low at the low temperatures, requiring a three- or four-wire bridge for measurement.

A sensor made by depositing a thin film of platinum on an insulating surface is much lower in cost than the wire-wound type. This type is very small and can be made to have a high resistance at low temperatures, which would make for less costly measuring equipment. However, what is not known is the degree of reproducibility between individual sensors.

Using good quality, interchangeable platinum thermometers is still generally limited to special applications because of the high cost. The cheaper, less precision types could prove to be more applicable for numerous measurements if interchangeable units requiring limited calibration can be made. A specially designed bridge signal conditioning device would be one method for providing all the inputs to a multichannel readout instrument.

4.2.2 Semiconductors

Semiconductor thermometers include those which have a basic element made from material that has less resistance than an insulator but more resistance than a conductor or so-called metallic resistance thermometer. Carbon, metallic oxides, and doped germanium are the most common semiconductors that have been investigated for cryogenic temperatures. All three have the same basic characteristics of negative temperature coefficient, extreme nonlinearities, and increased sensitivities at the lower temperatures (see Fig. 20). Common difficulties in making sensors with these elements are attachment of electrical leads to the materials and providing a strain-free mount that is rugged enough to withstand some vibration.

Although there have been some specially designed and built sensors, work with carbon has mostly been with some form of standard electrical, carbon-composition resistor. The standard insulation was usually removed and replaced by another in an effort to increase the thermal contact to the carbon and in an attempt to reduce thermal stresses which affect repeatability.

Metallic oxides, more commonly known as thermistors, have such temperature resistance characteristics that the resistance is too large at the lower temperatures for normal measurement means and is approaching insulation resistance values. Thermistors are then generally limited to the liquid nitrogen temperatures.

Even though the above sensors are readily available and cheap, the germanium sensors are more stable and repeatable and, therefore, more suitable for use. During the past two or three years, there has been considerable work with germanium to develop it into a cryogenic sensor. Pure germanium does not have the proper characteristics, but with small amounts of impurities, such as indium or similar materials, it begins to exhibit favorable characteristics. Most of the work has been in finding the amount and type of impurity to add that will increase the usable range and linearity, developing techniques to reproduce similar elements, and determining a suitable strain-free mount.

Of all the sensors for cryogenic temperatures, germanium and other semiconductors such as silicon and, perhaps, gallium-arsenide have possibly more potential and latitude in their development and use because of the manner in which their temperature characteristics can be altered. However, at this time, these elements cannot be interchanged, are useful over a limited range, are expensive, and require a complete calibration. These characteristics will limit their use primarily to special applications.

4.2.3 Gas Thermometers

Included in this class with the normal gas thermometer is the vapor-pressure thermometer since both are similar in design and have a pressure versus temperature calibration. For either type a small volume or bulb is required within the desired measurement region connected to a pressure-measuring system by a small capillary tube.

Although other instruments are used for interpolation of most temperatures, they are based on the gas thermometer, the most accurate means yet devised for determining true thermodynamic temperature (Ref. 19). The measurements are based on the ideal gas law

$$pv = nRT$$

where n is the number of moles of gas, R the universal gas constant, T the temperature in °K, p the pressure, and v the volume of the thermometer bulb. Used in a constant volume system, this equation reduced to $T_2/T_1 = P_2/P_1$, giving the ratio of the absolute temperatures.

For precision measurements, the use of a gas thermometer is difficult and exacting, but for wide temperature range and less accuracy, a gas thermometer can be used, for example, to follow the initial cool-down of a helium cryostat and monitor the operation thereafter.

A vapor-pressure thermometer consists of a bulb filled partly with a liquid or solid and partly with vapor in equilibrium with the condensed phase. The vapor-pressure thermometer can be used for accurate measurements over the vapor-pressure range of the material used in the thermometer. These types of thermometers are limited for use in temperature regions where materials having applicable vapor pressure exist. One advantage is that no calibration is required because the vapor pressures of the usable materials are known.

When considering the use of a gas-filled thermometer, the accuracy and cost of a pressure-measuring system must also be considered. Although these thermometers are not usable for surface measurements within the chamber because of the required bulb and connecting tube, there are possible applications for monitoring and controlling the chamber refrigeration systems.

4.2.4 Thermocouples

Because of inherent inhomogenities and/or low sensitivities, thermocouples for use within the cryogenic region are primarily limited to copper versus constantan and copper versus gold - 2.1 atomic percent cobalt. As shown in Fig. 21, the thermoelectric power of thermocouples approaches zero as the temperature approaches absolute zero; therefore, the sensitivity (μv/°K) decreases as the temperature decreases. Because of this the useful lower limit of copper-constantan for measurement in chambers is near 60°K where the sensitivity has dropped to 13.9 μv/°K. Gold-cobalt thermocouple wire was especially designed by Leiden Laboratories for use at cryogenic temperatures where the sensitivity at 10°K of 9.4 μv/°K is much larger than any other known thermocouple (Ref. 20).

The advantages of thermocouples include low cost, simplicity, and availability, whereas the disadvantages are low sensitivity and the requirement for a reference junction. The calibration of thermocouples consists of checking the outputs of two or three junctions from each batch or roll of wire. When a great deal of wire would be needed, the manufacturer should be required to use some quality control to produce all the wire with the same thermoelectric characteristics.

Because of the decreased sensitivities and low signal level outputs, the use of thermocouples for cryogenic temperature measurements with an accuracy of $\pm$1°K must be done with some forethought. Spurious electromotive forces are generated when inhomogenities caused by chemical impurities and mechanical strain are located within a temperature gradient. One means of reducing these electromotive forces is to reduce the number of gradients by routing the wires through the most constant temperature region. A second reduction would be to use only reference grade wire as opposed to standard grade thermocouple lead wires, and third, make the wires continuous or with a minimum of splices between the measuring junction and the reference junction.

Because of the cost of gold-cobalt wire, its slight instability at higher temperatures, and for reduction of spurious electromotive forces, the reference junctions of the copper versus gold-cobalt thermocouples should be inside the chamber as near the measuring junction as possible. This will require that special reference junctions be designed that will operate satisfactorily within the chamber environment.

4.2.5 Application Considerations

To assume that a sensor, especially a simple one such as a thermocouple, will indicate the temperature of the region into which it has been inserted is a technique that can be very disappointing. The temperature indicated will always be the difference in temperature of heat received at the sensor and to that transferred away. At low temperatures and in a high vacuum where high thermal gradients can exist over short distances, the source and magnitude of these heats are not always considered or recognized.

The first step for proper temperature indication is to mount the sensor with the best thermal contact to the point of measurement. For surface measurements this should be by soldering, direct clamping, or screw threads. Although it is being done, the use of an epoxy cement for attachment should be done with care and should only be used when no other means are possible. Errors as large as 8 to 10°K have been observed as a result of attachment by epoxies which have poor thermal conductance in a vacuum.

For in-line or immersion measurements the elements can usually be exposed directly to the fluid or gas. When the elements must be sealed or shielded from direct contact with the fluid or gas, the thermal contact will be decreased, but by making the immersion length longer and by helium filling the surrounding element volume, the installation is usually adequate.

One source of error can be caused by heat being conducted through the electrical leads to the sensor. One means of eliminating this effect is to place a length of lead wire immediately before the sensor within the same temperature region - more commonly termed "tempering". Using small-diameter lead wire (28 AWG or smaller) lengths of 24 to 30 in. in intimate contact with a temperating region has been found to be adequate.

As shown in Figs. 22 and 23, the thermal conductivities of the higher conducting metals increase to a peak in the cryogenic temperature region, whereas the conductivity for insulators continually decreases. As shown in Fig. 24, the specific heat of the metals also decreases with temperature. These characteristics point out the definite need of tempering lead wires, and the use of insulators between the sensor element and the surface to which it is attached should be avoided.

Radiant energy can be reduced by using thermal shields. Since the amount of radiation is dependent on the temperature of the area that the sensor "sees", specific locations, such as near or opposite a solar simulator, will require more elaborate shielding.

4.3 RECOMMENDED PRACTICES

4.3.1 Surface Measurements – 60 to 150°K

For the normal measurements of 60- to 150-°K surfaces requiring ±1-°K accuracy, copper versus constantan thermocouples are the most acceptable sensors and are widely used. The use of such techniques as attachment by soldering, embedding or direct clamping, routing the lead wire through minimum gradient regions, having continuous runs of reference grade wire, and referencing to an accuracy of 0. 1°K will help produce the desired results. The supplier of the wire should be required to produce all of it with a close tolerance on the variation of the thermoelectric power between rolls or batches. Relative deviations for samples chosen at random should not be greater than 0. 5 percent over the 60- to 150-°K range.

Calibration of the wire can be accomplished by checking the output of one or two junctions for each roll at several temperatures within the range. From these points the complete scale can be predicted since any deviation from the standard Instrument Society of America (ISA) thermocouple tables will be constant, or, in other words, if there is a difference in thermoelectric output of the thermocouples, the calibration curves will normally remain parallel.

The reference junctions can be located outside the chamber and can be of standard manufacture. These junctions should be located with a minimum length of thermocouple wire outside the chamber. Low-loss shielded cable should be used from the reference junction to the recording instruments.

4.3.2 Surface Measurements – 10 to 30°K

At this time, copper versus gold-cobalt thermocouples, applied with a few exceptions in the same manner as the above type, are the preferred sensors for surface measurements in the 10- to 30-°K range. For best results, the reference junction should be located within the chamber, attached to a liquid nitrogen panel, and controlled at approximately 150°K. Attachment to the liquid nitrogen panels is feasible because the 10- to 30-°K (helium) panels will not normally be cooled until the thermal shield of nitrogen is established. The wire should be obtained from a single lot and, for samples chosen at random, the thermoelectric power should not be greater than 0.7 percent over the 10- to 30-°K region.

4.3.3 In-Line Measurements

Platinum thermometers can be used for in-line measurements where accuracies of better than ±1°K are required. A special bridge signal-conditioning instrument can be used before the readout equipment. A system of good-quality, interchangeable types of platinum thermometer probes is still rather expensive, but these thermometers are the most accurate and reproducible.

The platinum film sensors can be produced with high resistance values (up to 5000 ohms at 75°F) without an increase in size. This would permit lead and contact resistance to be neglected, and trimming resistors could be used to compensate for small differences between films. What is not known is whether or not the resistance-temperature characteristics are sufficiently reproducible between individual sensors to permit a general method of interpolation based on fixed-point calibrations.

Ideally, it would be desirable to know the temperature of all cryopanels within ±1°K. The number of sensors to implement this completely would be very large. In order to keep the number of measurements to a feasible amount, the locations of these sensors should be chosen assuming some symmetry in temperature distributions for similar panels. This would mean having several points located on a few chosen panels with limited measurements for the remainder. These panels with limited measurements should have sensors located on surfaces near all inlet and outlet lines with other locations near support members, restricted flow regions, etc. Any surfaces that are opposite to or in line with high radiant heat sources, such as the earthshine and albedo units, will require additional sensors.

4.4 LOW-TEMPERATURE SCALES AND STANDARDS

Until the advent and need for cryogenic temperature measurements in space chambers, cryogenic thermometry was limited to applied science and research projects because there were limited practical applications and the means to produce the temperatures were very expensive. These projects were accomplished under laboratory conditions requiring only a few temperature measurements. Even though the requirements and applications are changed, the information from this work has been very helpful and relied on heavily to produce practical and acceptable means of measurement in space chambers.

One of the major problems in the area of cryogenic temperature measurements is the need for extension of the International Temperature Scale to 0°K by fixing some temperatures in this region and adapting a suitable means of interpolation and extrapolation. The need for this is obvious. There are efforts being made which will no doubt lead to a solution of this problem.

As it now stands, the scale extends only to the boiling point of oxygen (-182.970°C) and has other fixed points at the freezing (0°C) and boiling (100°C) points of water, boiling point of sulphur (444.600°C), freezing point of silver (960.8°C), and the freezing point of gold (1063.0°C). To make the scale continuous, a standard platinum thermometer of specified purity and physical conditions is used for interpolation from -182.97 to 630.5°C. The scale from 630.5 to 1063°C is defined by a 10 percent rhodium-platinum against pure platinum thermocouple and above 1063°C is affected by means of a standard optical pyrometer (Ref. 16).

The National Bureau of Standards has taken one obvious step by extending the calibration of the platinum resistance thermometer to the limit of its usefulness. They have calibrated six thermometers against a primary standard helium gas thermometer from 11 to 90°K to be their transfer standards. The estimated accuracy is ±0.02°K (Ref. 17). Intercomparisons of these from time to time have shown them to be very stable and repeatable.

The National Bureau of Standards has recently refined the ultrasonic thermometer to the point where temperature measurements in the range of 2 to 20°K (Ref. 18) can be made with great accuracy and precision. Based on the determination of the speed of sound in helium gas, the ultrasonic thermometer is expected to establish an absolute temperature scale in the region from 4 to 14°K and to provide the basis for the calibration of germanium resistance thermometers.

In order that each facility within the U. S. can have a common reference scale, primary or transfer standards used should have a direct comparison to the National Bureau of Standards. This is done for the most part by major suppliers and users of such equipment, but it is important enough to be mentioned.

5.0 TEST VEHICLE INSTRUMENTATION

The existence of the space chamber, as that of other ground test facilities, is justified by the usefulness of the information it produces on the performance of the vehicle under test. Test durations of several weeks are anticipated for some programs, and once altitude conditions have been established, ready access to the inside of the chamber for repairs, calibrations, or adjustments is not possible. For this reason, consideration must be given to redundant monitoring of some of the more critical data channels.

Typically, it is expected that temperature data will be of primary importance in orbit simulation tests; several hundred measurements will not be an uncommon requirement. Lesser numbers of pressures, events, positions, currents, etc., must also be observed, indicating that the data acquisition equipment may reasonably be expected to accommodate 500 to 1000 parameters. Man-rated chambers, now being contemplated, will require additional voice communication and biomedical monitoring facilities to provide maximum protection for the occupants. As advanced facilities are developed with nuclear, magnetic, or other possible simulation capabilities, additional instrumentation with more stringent operational specifications must necessarily be included.

5.1 DATA TRANSMISSION TECHNIQUES

The functional requirements of the space chamber data acquisition equipment are not unlike those of other test facilities. That is, the signal outputs from calibrated transducers or sensing devices must be conveyed to appropriate recording equipment where they are displayed or otherwise made available for further processing. Usually, digital conversion equipment is provided to prepare the data for entry into an electronic computer.

If only fixed test vehicles are involved, the complete instrumentation system may be located outside the chamber. Access to the vehicle sensors is made by direct cabling through connector penetrations in the chamber walls.

However, chambers designed for orbit simulation testing are typically fitted with bearing-supported vehicle mounts which permit continuous movement of the test vehicle around one or more axes. Orbit simulation is thus achieved by programming the vehicle attitude and rate of motion past the radiation lamps and cold-walled sections of the chamber. This rotational freedom places an added restriction on the implementation of the test vehicle instrumentation. Conventional hard-line connections can no longer be accomplished, and methods must be found for gaining access to the transducers and other sensing devices located on the test vehicle.

Various techniques that have been suggested are presented here together with some of their most evident advantages and deficiencies. Each will likely be useful after the capabilities of existing and future test facilities are developed. Since previous experience in this area is limited, much of the information presented is based on present-day thinking rather than well-established fact.

5.1.1 Slack Loop Cables

In a slack loop or flexible cable installation, hard lines are carried directly to the sensors on the test vehicles. As the vehicle revolves, the cables are wound in a coil around the axis of rotation. Especially developed pre-wound cables have been manufactured which would permit a large number of revolutions in one direction before rewinding. There is a definite limitation on the number of cables that could be accommodated in this manner, and the installation becomes cumbersome if more than one axis of rotation is involved. However, it is likely that this arrangement will have limited application in some test programs.

5.1.2 Slip Rings

Slip rings, by their nature, would appear to present a very logical solution to the access problem. Certainly it is practical to construct large slip-ring assemblies that can accommodate the multi-channel requirements of present space chambers. In fact, they are currently being used in power circuits and high-level signal applications. However, the capabilities of these assemblies in millivolt-level circuits have been proven only in non-vacuum environments. An acceptable lubricating scheme capable of extending the expected useful life of such assemblies beyond several hundred hours at 10^{-7} torr has yet to be demonstrated. Work with various material combinations and reservoir lubricating and sealing techniques is progressing, and one manufacturer has stated that a 5000-contact slip-ring package for low-level signal voltage is foreseeable. A roughly estimated cost (Ref. 21) of this package is $250, 000 to $500, 000.

By using slip rings the advantages of a hard-line installation are retained. Each transducer output is routed through a chamber penetration to conventional signal-conditioning and processing instrumentation located outside the chamber. Since this equipment is accessible, repair or replacement can be accomplished in the event of failure. The need for redundant instrumentation of critical data channels, that might otherwise be required, is thus eliminated.

Some caution must be observed in the selection of the cable to be used inside the chamber. Certain insulating and filler materials with excessive outgassing and absorbent properties, if used in quantity, would impose an unnecessary load on the chamber pumping facilities. Teflon insulated cables are now most widely used and appear to be the best selection.

The considerable bulk and expense of the multi-channel slip-ring installation may be reduced by on-board multiplexing. Many channels of data may then be transmitted in time sequence through one set of slip rings, while a lesser number of more critical or wide bandwidth signals are routed individually through separate slip rings. This approach can be extended further to include signal-conditioning and analog-to-digital conversion equipment inside the chamber. The performance requirements of the slip rings are now greatly reduced since a much higher noise level can be tolerated with the digital data. These advantages must be weighed against the problems of equipment inaccessibility in the determination of any particular installation. However, until the economy and reliability of large slip-ring assemblies have been demonstrated, a certain amount of in-chamber equipment must be considered a necessity.

5.1.3 Radio Telemetry

Radio telemetry offers another approach to the access problems - one that could eliminate the need for both slip rings and feedthrough cables. Also, it provides the additional advantage of compatibility with on-board test vehicle airborne instrumentation, which must necessarily be telemetry. This latter fact must be given serious consideration. Certainly while the vehicle is under test, the chamber user will have a definite interest in those parameters that he has selected to monitor during actual flight. Furthermore, the simulation test may very well be serving as an additional check on the performance of the vehicle instrumentation itself. It follows, therefore, that external equipment must be provided for communication with the vehicle. The advantages of supplying a versatile, telemetry-data-handling capability as a chamber utility are evident. Such capability is not gained without difficulty since the variety in present telemetering equipment makes a truly universal system hard to specify. A reasonable compromise should be obtainable, however, especially if an accurate projection of the mission of the chamber is available.

There are a number of operational problems involved with a telemetry system that should be discussed. First, the power supply requirements of the in-chamber equipment must be satisfied. Batteries have a definite application, but their usefulness is limited in extended tests unless recharging facilities are provided. General Electric (GE) has installed a movable ram for this purpose in one of their Valley Forge chambers. At necessary intervals the ram is extended to mate with connectors on the vehicle. Battery recharging is accomplished, and the ram is again retracted into a well in the chamber wall. This rather elaborate approach was necessitated by the requirement that the test vehicle have complete freedom of movement during the programmed test periods.

Solar panels appear to be practical only to the extent that they are provided with the test vehicle. Present size and cost prohibit their use as a power source for auxiliary vehicle instrumentation. The alternative methods would necessarily employ slip rings or the flexible cable arrangement previously discussed.

A second questionable aspect of the telemetry approach involves the transmission of the radio-frequency carrier. Problems arising from reflection and standing waves within the chamber have been suggested. Others have indicated that detrimental impedance mismatches may be created by the proximity of the transmitting antenna to the receiving antenna and various other chamber structures. Motion of the test vehicle introduces a further complication by adding a component of variation to conditions already existent. Formidable as these problems may appear, evidence is available to support the suggestion that radio-frequency telemetry can indeed be useful for space chamber applications. This is further substantiated by the fact that essentially all major U. S. facilities are either now using or contemplating the future use of telemetry systems.

Investigations are being conducted to determine the severity of the transmission problems. Work at GE and at the Arnold Center has established that the effects of reflection on pulse-modulated carrier reception are insignificant at pulse repetition rates up to 200 kc. GE has observed the variation of antenna impedance as a function of chamber location and is planning further study in this area. Should their results indicate that these variations would be detrimental to sharply tuned transmitter circuits, they are considering the placement of absorbent curtains within the chamber to reduce reflections. The need for such measures may be eliminated if broadly tuned transmitter circuits, less critical to impedance changes, are permissible on the vehicle under test. Data measurements are being made using such equipment in experimental chambers at the Arnold Center.

Noise and interference generated by nearby electrical equipment present another possible trouble source. The fact that radio-frequency energy can be readily propagated out of the chamber carries the additional implication that external energies can just as readily be received within and cause possible interference with the data transmission. Carbon arc solar simulator arrays being installed in some chambers could be particularly troublesome in this respect. Adequate filtering and shielding, together with careful selection of the carrier frequencies and power levels, are suggested combatants of the interference problem. Utilization of a coaxial cable rather than a space link for transmission of the radio-frequency carrier from within the chamber presents an alternative which may eliminate both the propagation and interference problems. This approach has been suggested by the Lockheed Missile and Space Division (Ref. 21) for instrumentation of a proposed 160-ft-diam environmental chamber. Access to the moving vehicle would be accomplished with a rotary coaxial joint at each axis.

5.1.4 Other Transmission Methods

Various other methods of data transmission, such as rotary waveguides, sonics, rotary transformers, and optical techniques, have been investigated. Electro-Optical Systems, Inc. (EOS) recently reported (Ref. 22) the results of a study on these plus the radio-frequency and hard-line systems discussed above. Recommendations are made favoring pulse-amplitude-modulated (PAM) microwave telemetry transmitted through waveguides. Advantages listed are the wide bandwidth capabilities (several mc) and the low transmission power requirements. A dual-channel, rotary waveguide joint specified for this system was recently tested at the AEDC and performed satisfactorily in the simulation chamber environment. The cost of the increased transmission efficiency of the microwave system is represented by the added complexity of the x-band frequency translation equipment required.

5.2 TYPICAL DATA SYSTEM

Among the several present-day environmental test facilities in the U.S., some are completed, and operating experience with chamber-oriented vehicle instrumentation systems has been accumulated. The final specifications for other facilities that are in the planning or construction stage have not been determined because of the particular requirements at each installation. As a conclusion to this discussion, brief reference is made to a system which is planned for the Aerospace Systems Environmental Chamber, Mark I (Fig. 25), at AEDC.

5.2.1 In-Chamber Data Acquisition Equipment

Radio-frequency telemetry has been selected as the most suitable method of data transmission from within the chamber. It is planned to provide facility data acquisition equipment that will supplement or back-up instrumentation already designed into the test vehicle. This auxiliary equipment will include a PCM telemetry system containing all components necessary for scanning, encoding, modulating, and transmitting data to a ground station located outside of the chamber. In a typical configuration, each input channel is converted to an 9-bit binary equivalent at a scanning rate of approximately 10,000 channels per second. As many as 1000 low-frequency data channels may be accommodated by employing subcommutation (Fig. 26).

Two IRIG FM/FM links are to be provided to satisfy requirement for continuous monitoring of critical or higher frequency channels.

5.2.2 Telemetry Reception and Data-Processing System

A telemetry reception and data-processing system is to be employed outside the test chamber for the purpose of receiving and processing telemetry data, analog signals from transducers transmitted over cables, and the subsequent digitizing and recording of these data (Fig. 27).

Telemetry Interface: This includes receiving and demodulation equipment for three radio-frequency transmission links. A sufficient number of channel selectors and discriminators shall be provided for accommodation of 20 IRIG standard subcarrier bands.

Postdetection System: Includes complete facilities for simultaneous recording of three channels of telemetry information. Data to be recorded are derived from the telemetry receiver outputs after demodulation. Playback of such recorded data through the data-processing system will be possible. The tape transport will be a 7-track system with the extra tracks to be used for voice, time reference signals, or possible expansion to more than three telemetry links.

A particular advantage of this system is that it permits direct on-line recording of the telemetry data. Should difficulty occur in the data-recovery system or should reruns be required, the raw data are available for repeated playback.

Data Processing: Accepts data from external analog sources as well as that applicable from the telemetry interface. Input facilities include 20 high-level channels (5-v full-scale), plus 30 low-level channels (40 mv full-scale) that may be used for auxiliary hard-line information. PCM data are to be recovered and reassembled in its original form on an additional channel. Pulse amplitude (PAM) and pulse duration (PDM) data must also be acceptable to provide versatility and compatibility with user's on-board equipment. All data are scanned in time sequence and converted to BCD code for recording on magnetic tape. The tape format is to be consistent with that required for entry into the IBM 7074 computer.

Monitoring Equipment: Oscillographs will be provided for recording 20 channels of analog data on a real-time basis plus a bar scope for display of the PCM, PAM, and PDM information. Also, a tabulator readout is to be available for preliminary setup, calibration, and maintenance purposes.

6.0 CONCLUSIONS

Vacuum measurements in space simulators are most generally performed with the Alphatron, Pirani, CVC Magnevac, and thermocouple gages where applicable in the 10^{-3}- to 760-torr range. Below 10^{-3} torr, cold-cathode discharge gages are used to 10^{-7}, and Bayard-Alpert-type hot-cathode ionization gages are used to 10^{-9} torr. Both the nude-mounted and tubulated types are employed, but it is generally felt that the nude gages give better results. Ionization gages are frequently mounted both on the chamber wall and on the vehicle.

Mass spectrometers most commonly employed are the small magnetic deflection type, commercially referred to as residual gas analyzers, with unit resolution to about 50 mass units, and capable of detecting about 10^{-11}-torr partial pressure.

Pressure calibrations down to 1 μ are usually performed with mercury manometers including the McLeod gage. Below 10^{-3} torr, calibrations of ionization gages are most frequently performed with sensitive McLeod gages to 10^{-5} torr with an accuracy of approximately ±10 percent. The calibration is then extrapolated to the lower pressures. At the Arnold Center, ionization gage calibrations are performed by the porous-plug-calibrated-orifice technique to 10^{-7} torr with an accuracy of about ±10 percent (Ref. 10). Plans are being made at AEDC to extend this lower limit to 10^{-8} torr and to include provisions for determining mass spectrometer sensitivities.

For spectral distribution measurements a spectrophotometer and/or radiometers equipped with optical filters are most generally used. Total intensity measurements are made with thermopile detectors (radiometers), whereas uniformity measurements are made using a radiometer for absolute values; photo-detectors are used for fast scans that yield relative uniformity. No direct collimation measurement apparatus is available, and measurement techniques have been disappointing; however, the parabolic mirror method, as shown in Fig. 16a, and the long blackened tube method (Fig. 16b) are presently being used.

Cryogenic sensors that are presently used are copper versus constantan thermocouples for the 60- to 150-°K surface temperatures, and gold-cobalt versus copper and semiconductors for 10- to 30°K surface temperatures. Vapor-pressure thermometers, platinum resistance probes, and semiconductor probes are used for in-line measurements of liquid and gaseous cryogenic refrigerants.

Data acquisition systems for acquiring data from the sensors vary from the on-line computer system to a data logger and annunciator, as shown in Fig. 18. Varying numbers and types of monitoring instruments are used, including plotters, punched cards and/or tape, bar graphs, and printers, depending on the complexity of the system.

Vehicle instrumentation at major environmental facilities throughout the U. S. does not differ significantly. Hard-line systems are used extensively in chambers testing stationary vehicles. Supplemental telemetry systems may also be employed with carrier transmission being accomplished through coaxial cables. Some slip rings are being used for high-level signals where access is complicated by vehicle motion. Also, most of these facilities are either now using or considering the future use of telemetry. Radio-frequency propagation of telemetry carriers from within the chamber has many advantages which are currently being developed. Access through rotary coaxial or waveguide joints may also be used in applications where local interference problems are significant.

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1. Mechanical, Mercury, and Liquid Manometers-Visual Readout Only
2. Bourdon Tube and Diaphragm-Bellows Types with Strain Gage or Variable Reluctance Pickoffs
3. Diaphragm Manometer with Capacitance Pickoff
4. Thermocouple Gages
5. Pirani Gages and Similar Types
6. Alphatron Ionization Gages
7. Phillips Cold-Cathode Ionization Gages
8. Hot-Cathode Ionization Gages without Magnetic Field
9. Cold-Cathode Ionization Gages with Magnetic Field
10. Mass Spectrometers

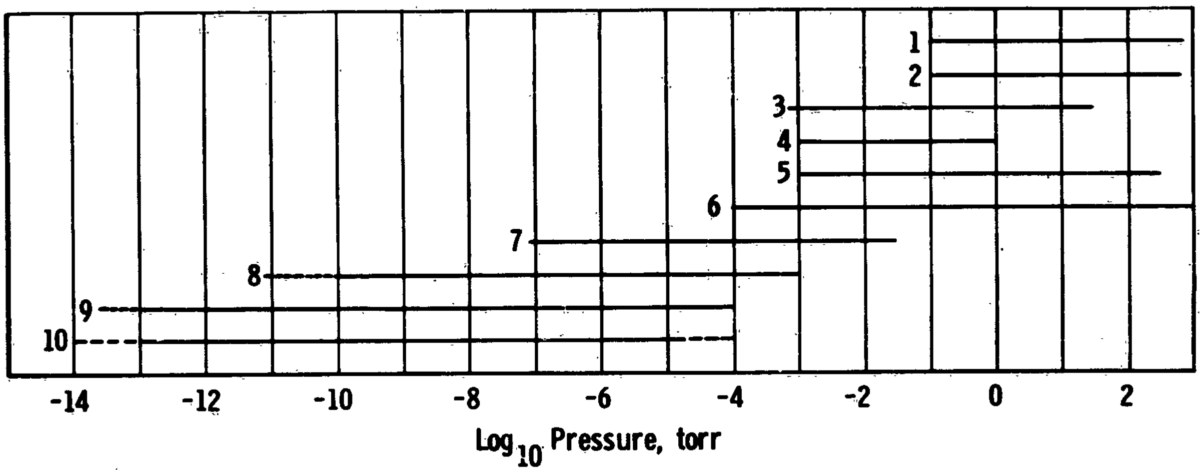


Fig. 1 Types and Ranges of Vacuum Measuring Devices Useful in Space Simulation

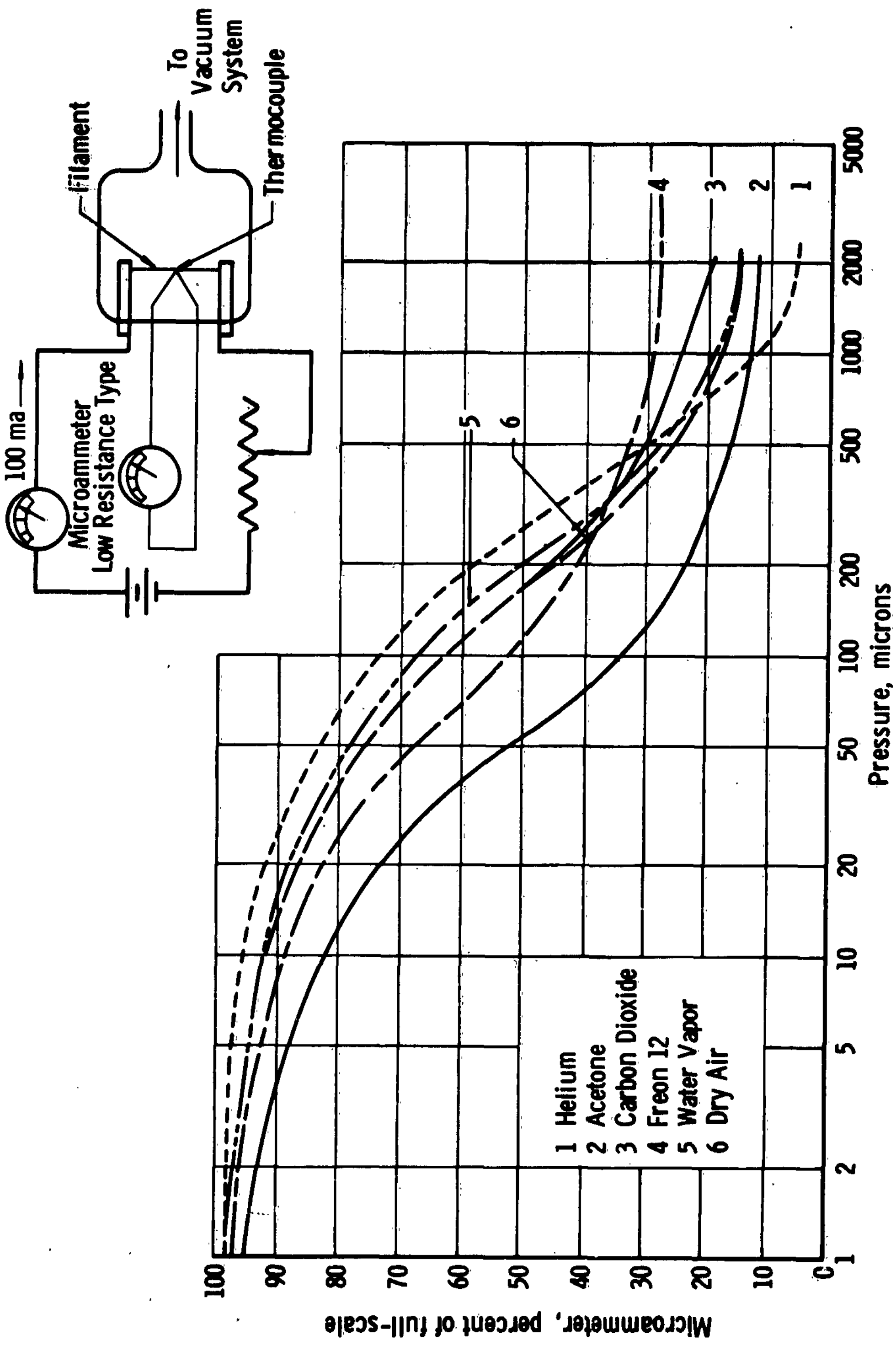


Fig. 2 Thermocouple Gage Schematic and Relative Gas Sensitivities

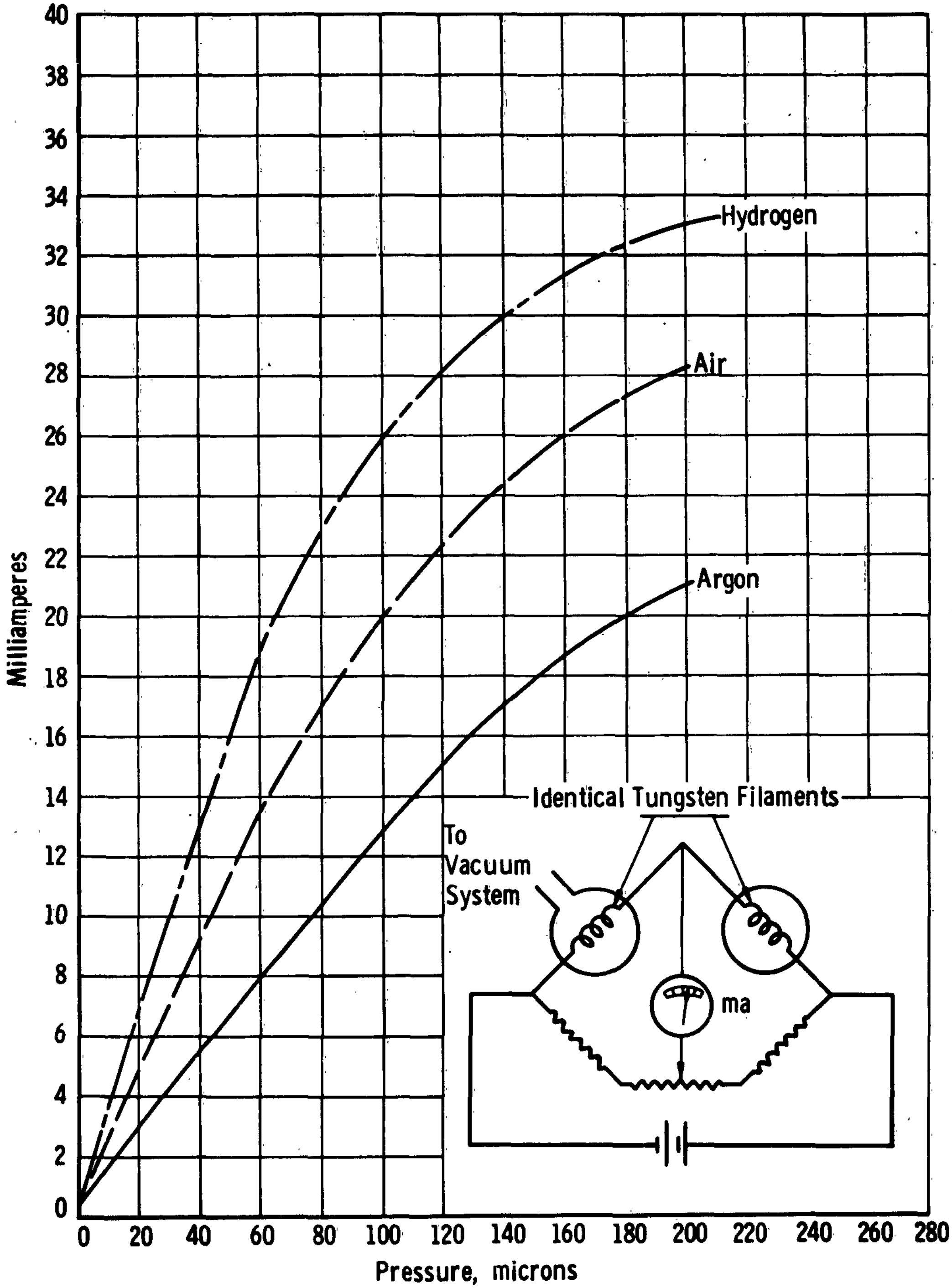
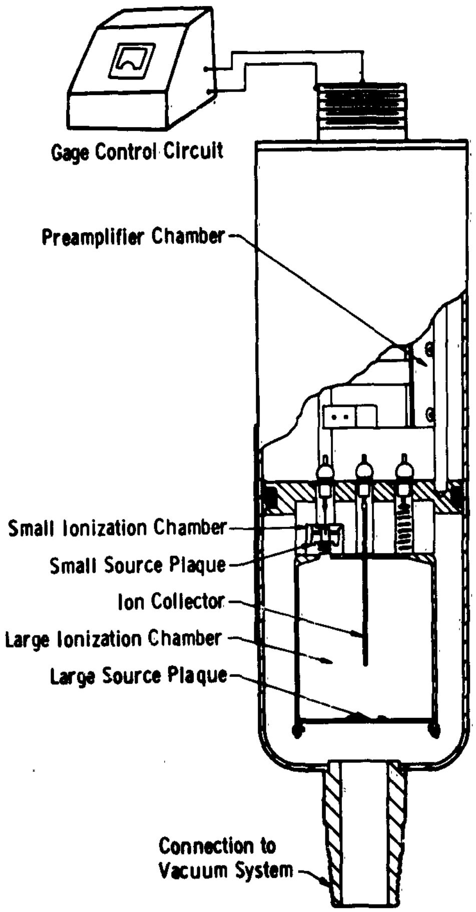
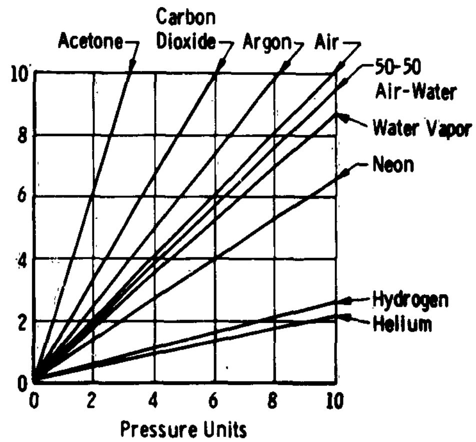


Fig. 3 Pirani Gage Schematic and Relative Gas Sensitivities



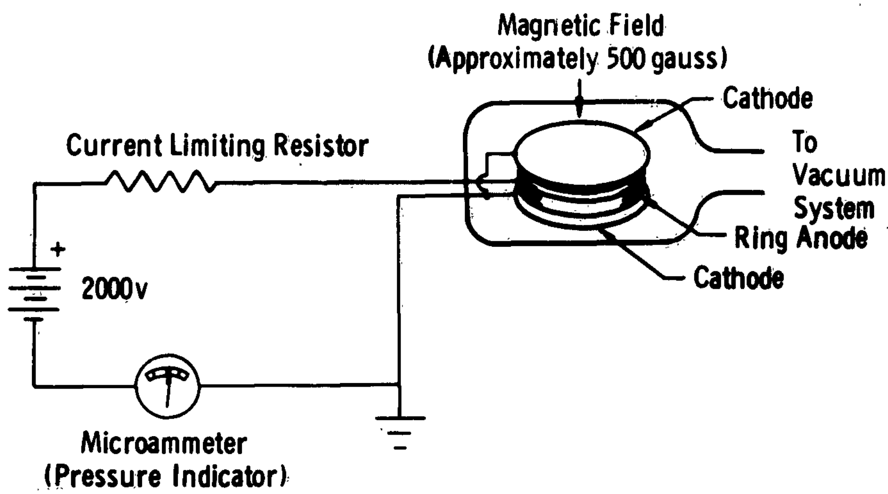


Relative Response*

Acetone Vapor	3.14
Carbon Dioxide	1.58
Argon	1.19
Air	1.00
Water Vapor	0.86
Neon	0.64
Hydrogen	0.25
Helium	0.21

*Relative response figures and curves are not exactly accurate in the highest pressure ranges for gases heavier than air. Data supplied by NRC.

Fig. 4 Alphatron Ionization Gage and Relative Gas Sensitivities

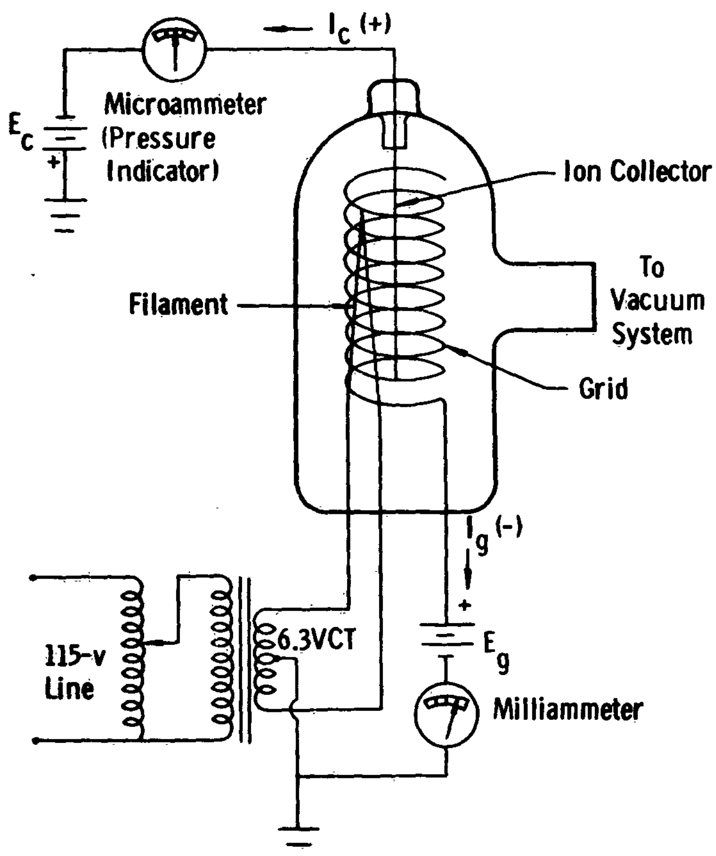


Typical Sensitivity Factor

Gas	Sensitivity Factor, f
Helium	0.21
Hydrogen	0.40
Carbon Monoxide	0.95
Nitrogen	1.0
Air (Dry)	1.0
Oxygen	1.23
Carbon Dioxide	1.23
Argon	1.39

Note: To find true pressure, the gage reading is divided by f. (Data supplied by Consolidated Vacuum Corporation.)

Fig. 5 Phillips (Penning) Cold-Cathode Ionization Gage Schematic and Relative Gas Sensitivities

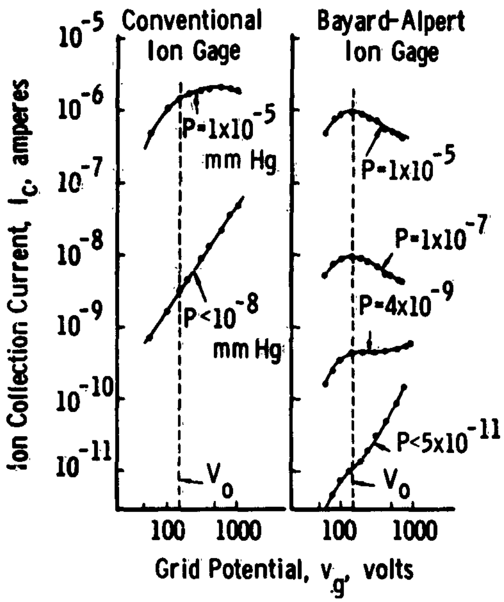


Gas or Vapor	Gauge Factor
N_2	1.0
O_2	1.18
H_2	2.0
H_e	6.2
H_2O	1.12
CO_2	0.73
CO	0.94
Hg	0.29
A	0.84
Ne	4.2
Kr	0.53
Xe	0.37
"Silicone" Pump Oil	0.37
"Octoil" Pump Oil	0.2
Air	1.1

Note: Multiply ion gage reading by factor shown for correct pressure.

Data supplied by VEECO Vacuum Corporation.

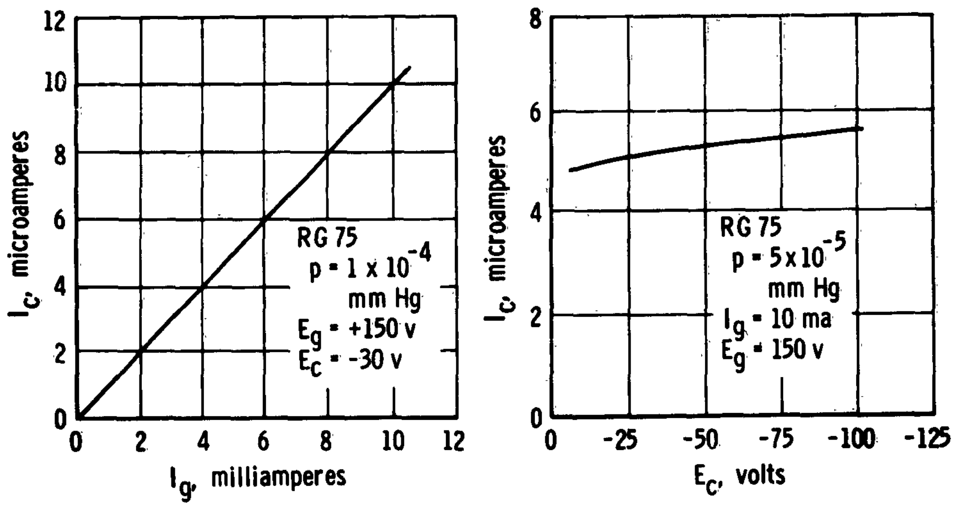
Fig. 6 Hot-Cathode Ionization Gage (Bayard-Alpert Type) and Control Unit Schematic and Relative Gas Sensitivities



a. Conventional Gage (RCA Type 1949)

b. Bayard-Alpert Gage

Fig. 7 Typical Data for Ion Gages

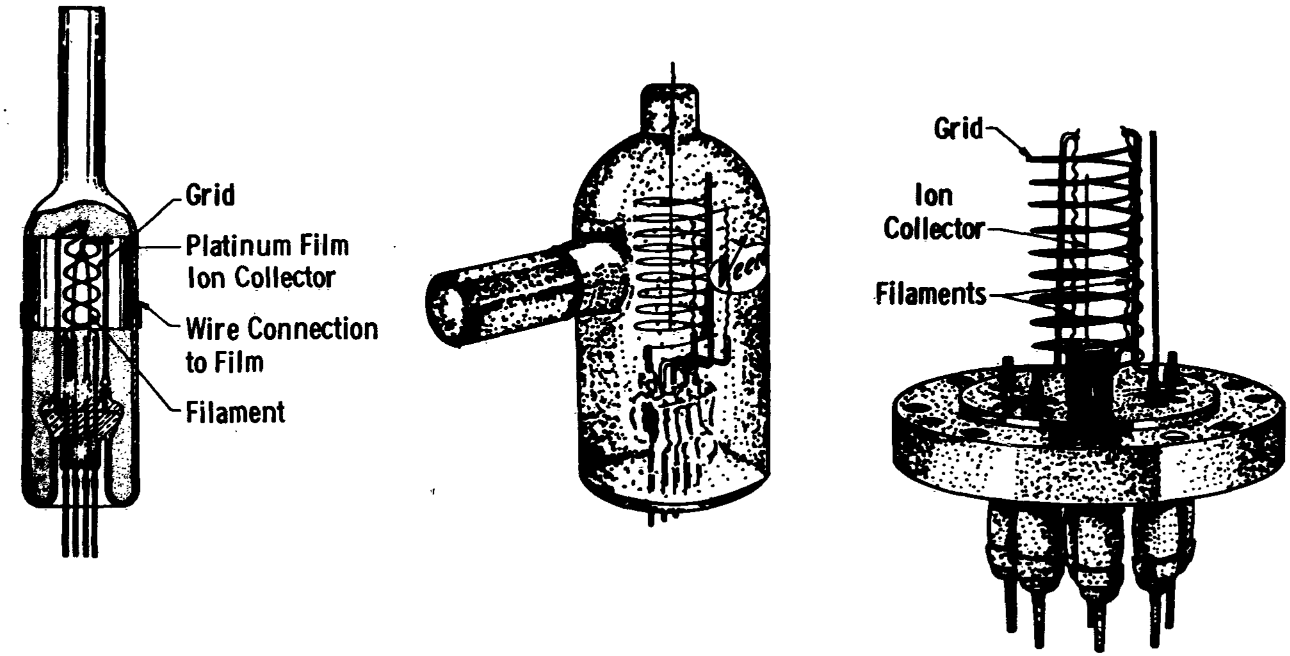


(Data supplied by VEECO Vacuum Corp., Long Island, N. Y.)

a. Collector Current vs Grid Current

b. Collector Current vs Collector Voltage

Fig. 8 Typical Ionization Gage Characteristics of an Inverted Hot-Cathode Ionization Gage



a. Normal Triode Ion Gage

b. Tubulated Bayard-Alpert Gage

c. Nude-Mounting Bayard-Alpert Gage

Fig. 9 Typical Hot-Cathode Ionization Gages

Manufacturer and Model	Type	Mass Range with Unit Resolution	Minimum Detectable Partial Pressure and Total Pressure Limit	Minimum Scan Time	Electron Multiplier	Bakeout Temp.	Readout Mode
Bendix Corporation Model 17-210	Time-of-Flight	2-204	1×10^{-12} torr 1×10^{-5}	100 μsec	Yes	200°C	Strip Chart Oscilloscope
General Electric Co. Model 514	90° Magnetic Deflection	2-50	1×10^{-13} 5×10^{-6}	45 sec	Yes	450°C	Strip Chart
Vacuum-Electronics Corporation Model GA-3	60° Magnetic Deflection	2-44	5×10^{-11} 1×10^{-5}	10 min	No	450°C	Strip Chart
Consolidated Electrodynamics Corporation Part 136000	180° Magnetic Deflection	2-150	1×10^{-12} 5×10^{-4}	20 min	No	250°C	Strip Chart
Consolidated Electrodynamics Corporation Type 21-612	180° Magnetic	2-20	1×10^{-9} 1×10^{-4}	5 min	No	450°C	Strip Chart
NRC Equipment Corporation Type 9505-164-91 Omegatron	r.f. Cyclotron	1-30	1×10^{-11} 1×10^{-6}	10 min	No	450°C	Strip Chart
Atlas-Werke A.G. Bremen-Abt. Mat. Massenfilter AMP 3	r.f. Mass Filter	2-100	5×10^{-11} 1×10^{-4}	--	No	450°C	Strip Chart Oscilloscope

Fig. 10 Summary of Typical Commercially Available Gas Analyzers

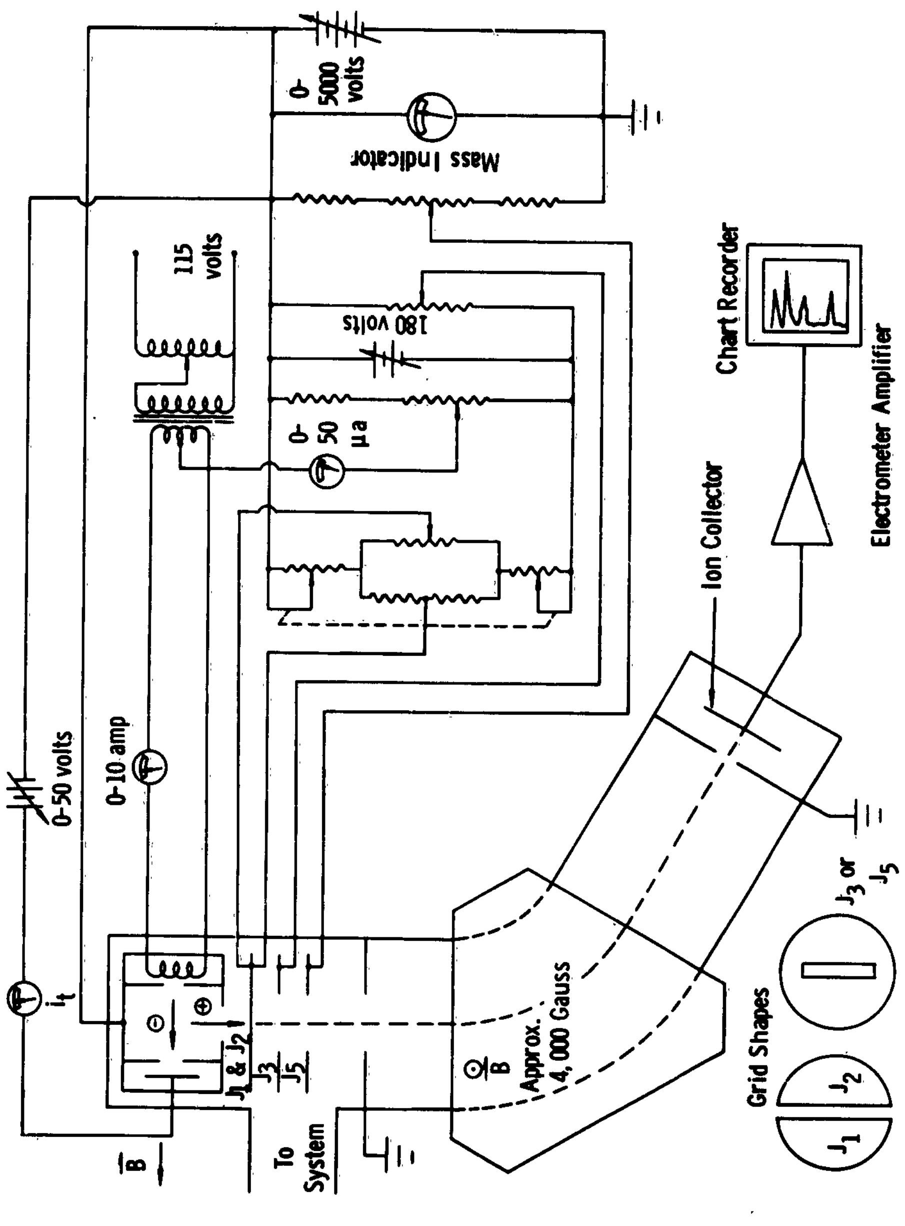


Fig. 11 Simplified Diagram of 60-deg Magnetic Deflection Mass Spectrometer with Nier Type Ion Source

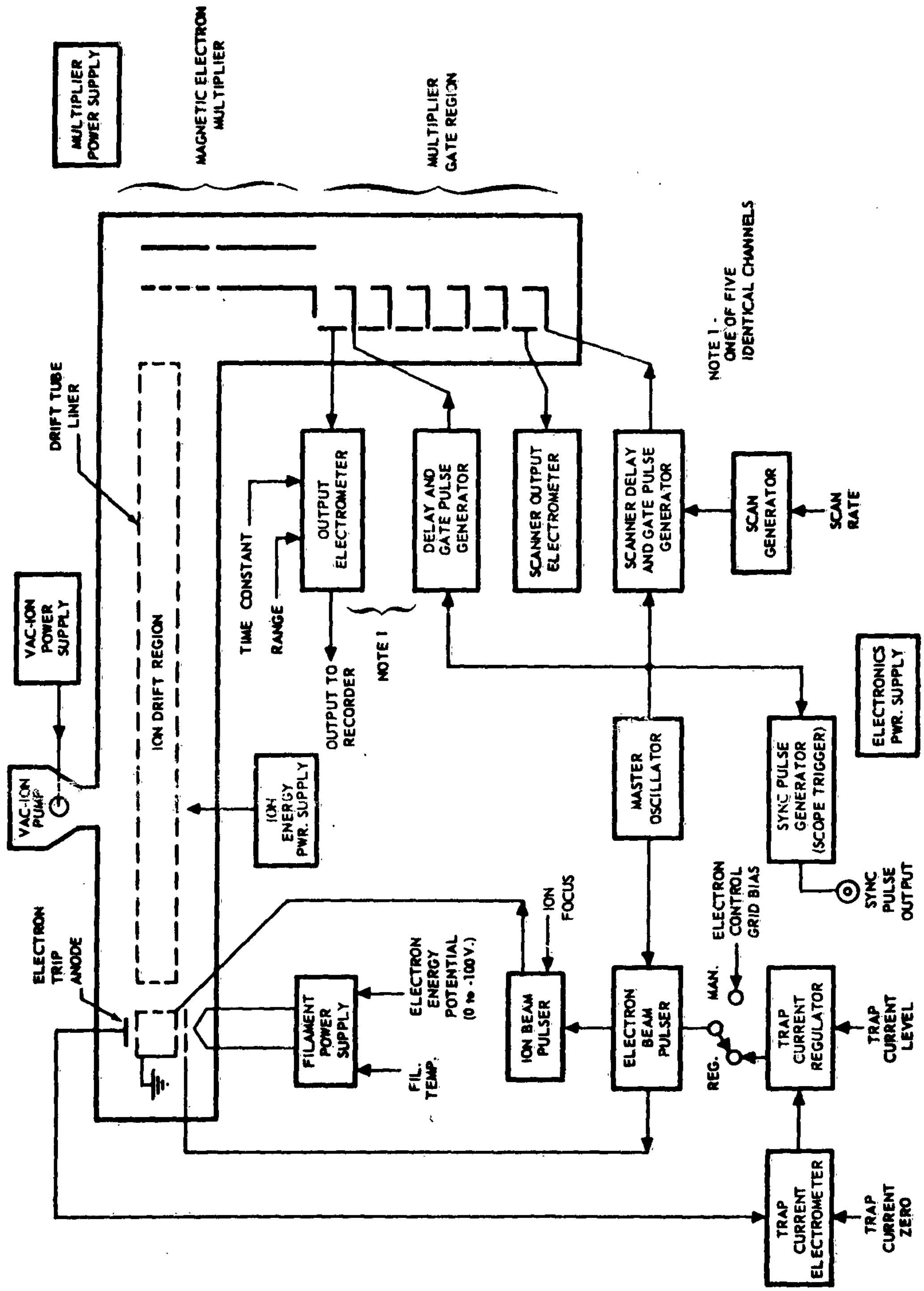


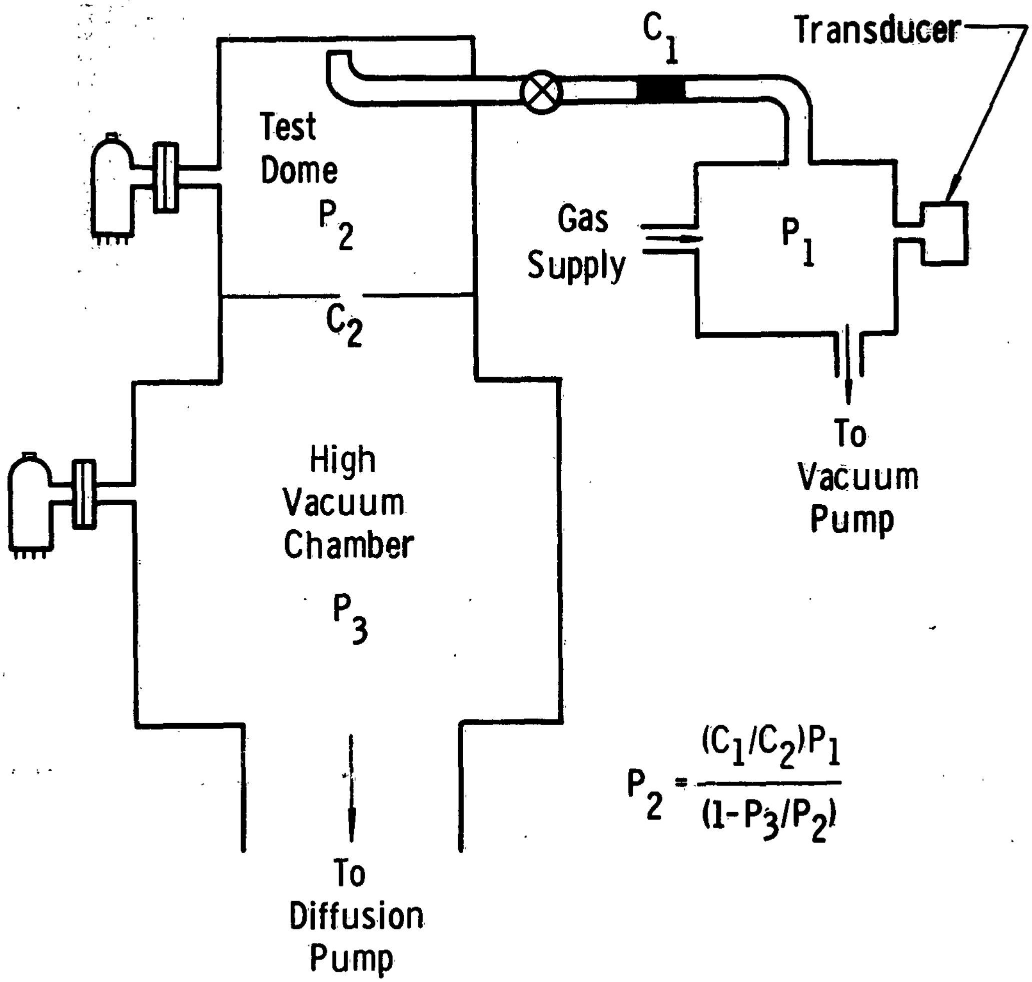
Fig. 12 Basic Elements of the Bendix Time-of-Flight Mass Spectrometer

Gas	Ion Species	Mass Number	Relative Abundance
H_2	H_2^+	2	100
He	He^+	4	100
CH_4	CH_4^+	16	100
	CH_3^+	15	80
	CH_2^+	14	12
	CH^+	13	5
	C	12	2
H_2O	HOH^+	18	100
	OH^+	17	30
	O^+	16	4
CO	$^{13}CO^+$	29	1
	$^{12}CO^+$	28	100
	O^+	16	3
	CO^{++}	14	1
	C^+	12	8
N_2	$^{15}N^{14}N$	29	0.7
	N_2	28	100
	N & N_2^{++}	14	4
NO	NO^+	30	100
	O^+	16	2
	NO^{++}	15	3
	N^+	14	11
O_2	O_2^+	32	100
	O^+, O_2^{++}	16	15
CO_2	$^{13}CO_2^+$	45	1
	$^{12}CO_2^+$	44	100
	CO^+	28	10
	CO_2^{++}	22	2
	O^+		
	C^+		

Gas	Ion Species	Mass Number	Relative Abundance
C_2H_6	$C_2H_6^+$	30	23
	$C_2H_5^+$	29	21
	$C_2H_4^+$	28	100
	$C_2H_3^+$	27	36
	$C_2H_2^+$	26	25
	C_2H^+	25	5
	C_2^+	24	1
	CH_3^+	15	5
	CH_2^+	14	4
	CH^+	13	2
	C^+	12	1
A	A^+	40	100
	A^{++}	20	10
C_3H_8	$C_3H_8^+$	44	27
	$C_3H_7^+$	43	23
	$C_3H_6^+$	42	6
	$C_3H_5^+$	41	14
	$C_3H_4^+$	40	3
	C_3H_3	39	21
	C_3H_2	38	7
	C_3H	37	4
	C_3	36	1
	C_2H_6	30	2
	C_2H_5	29	100
	C_2H_4	28	58
	C_2H_3	27	46
	C_2H_2	26	11
	C_2H	25	1
	CH_3	15	10
	CH_2	14	3
	CH	13	1

Note: These cracking patterns are typical of mass spectrometers with electron bombardment type ion sources. (To be used as a guide only). Data supplied by General Electric Company.

Fig. 13 Typical Cracking Patterns



$$P_2 = \frac{(C_1/C_2)P_1}{(1-P_3/P_2)}$$

Fig. 14 Ionization Gage Calibration System

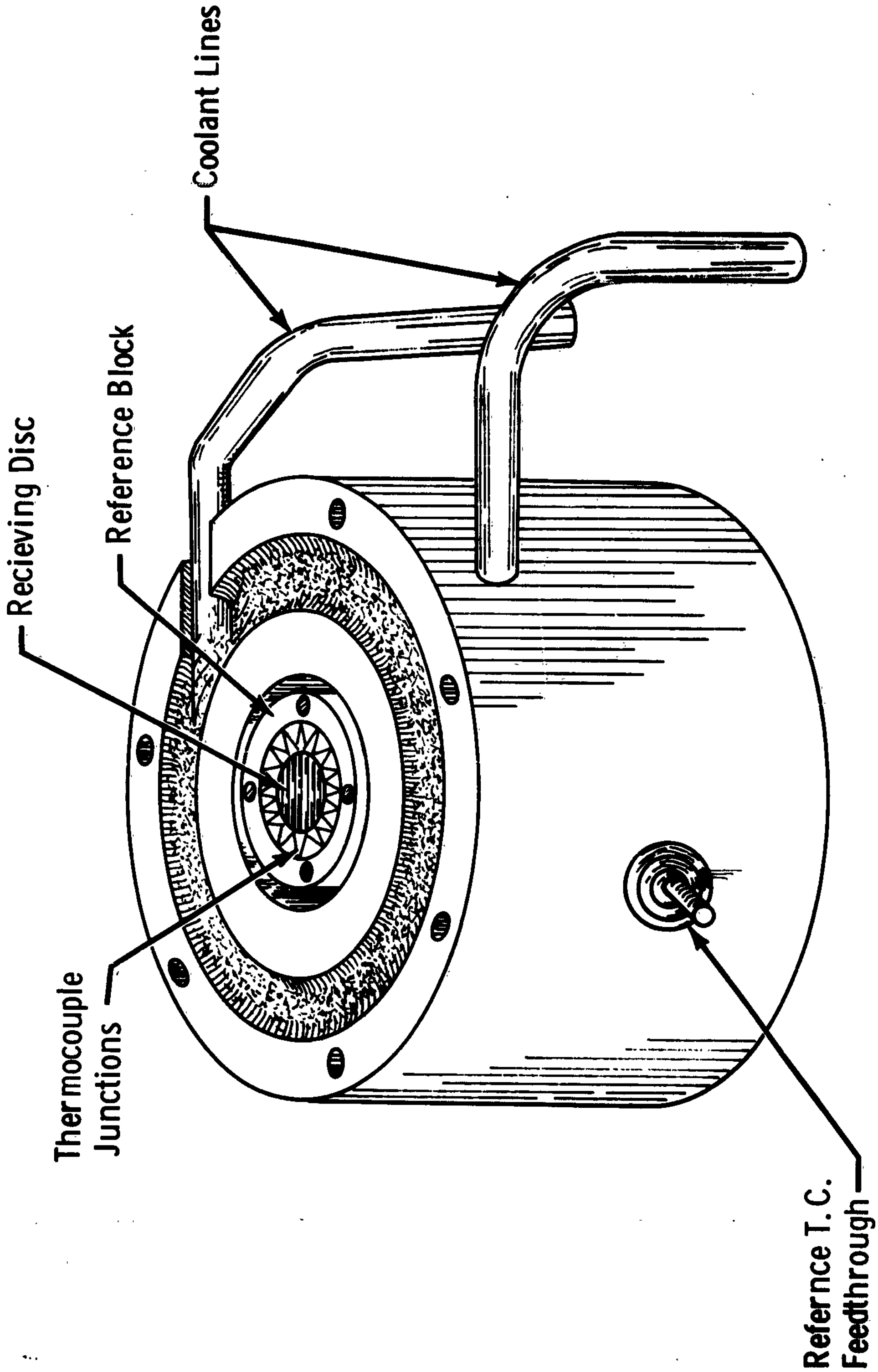


Fig. 15 Typical Radiometer

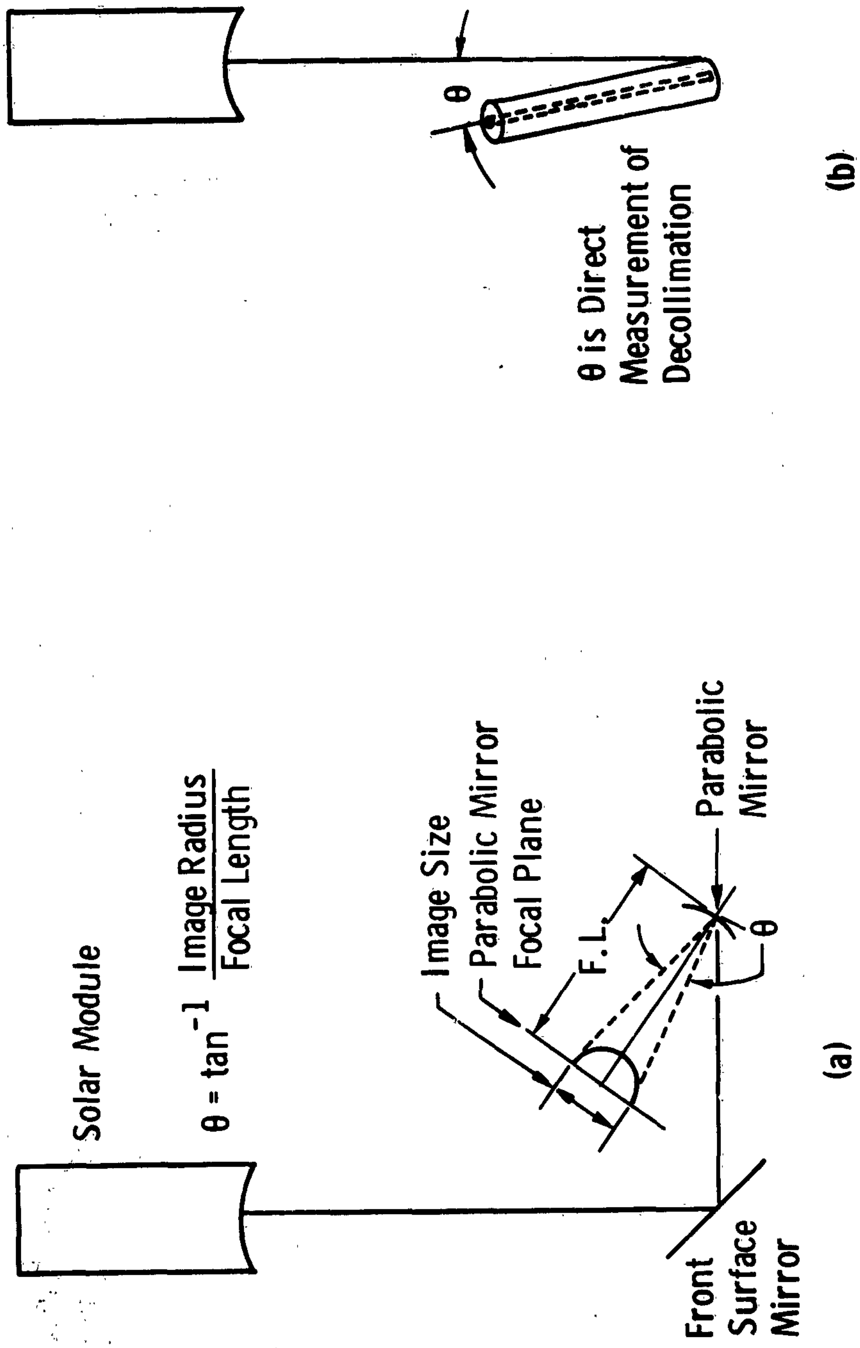


Fig. 16 Collimation Measurement

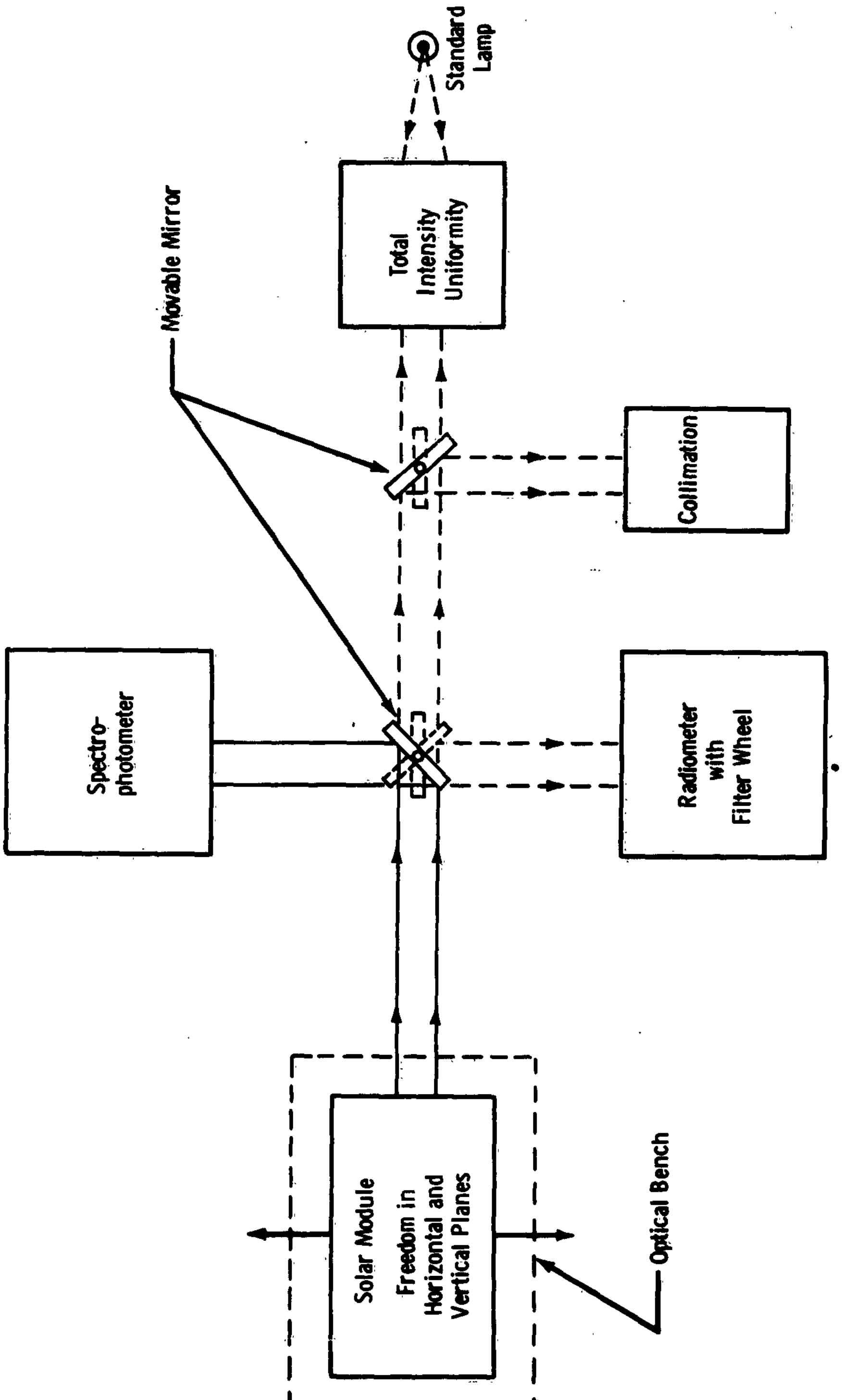


Fig. 17 Solar Module Calibration System

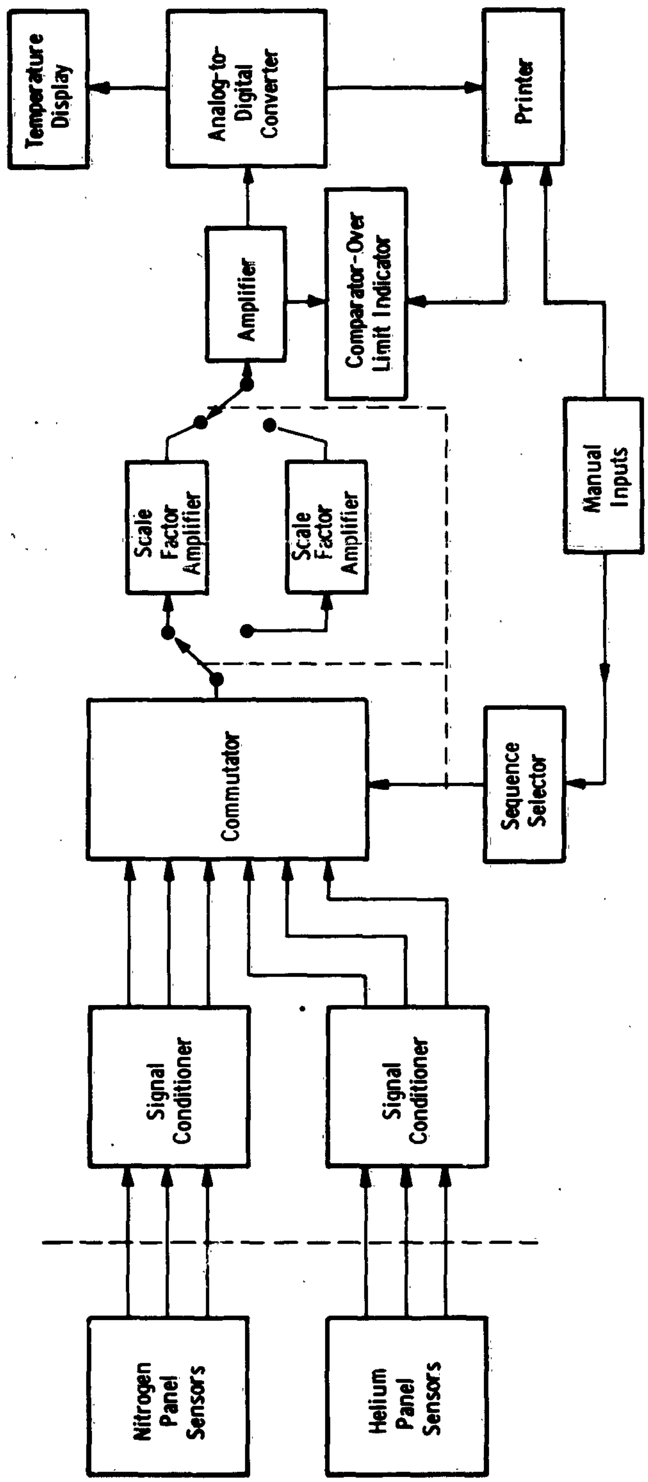
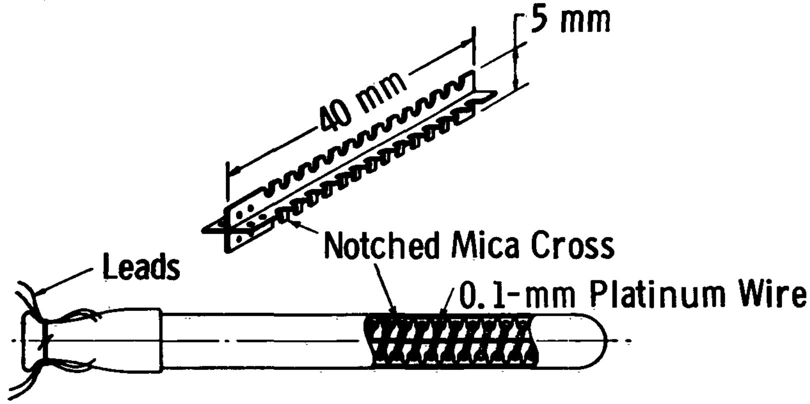
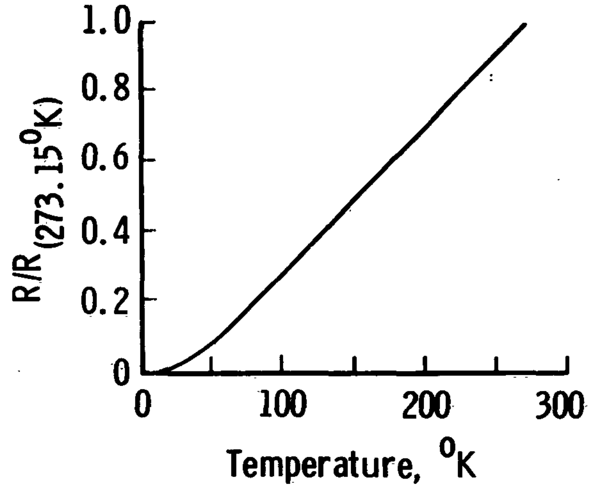


Fig. 18 Typical Data Acquisition/Annunciator System



a. Schematic



b. Resistance of Platinum as a Function of Temperature

Fig. 19 Capsule-Type, Strain-Free, Platinum Resistance Thermometers

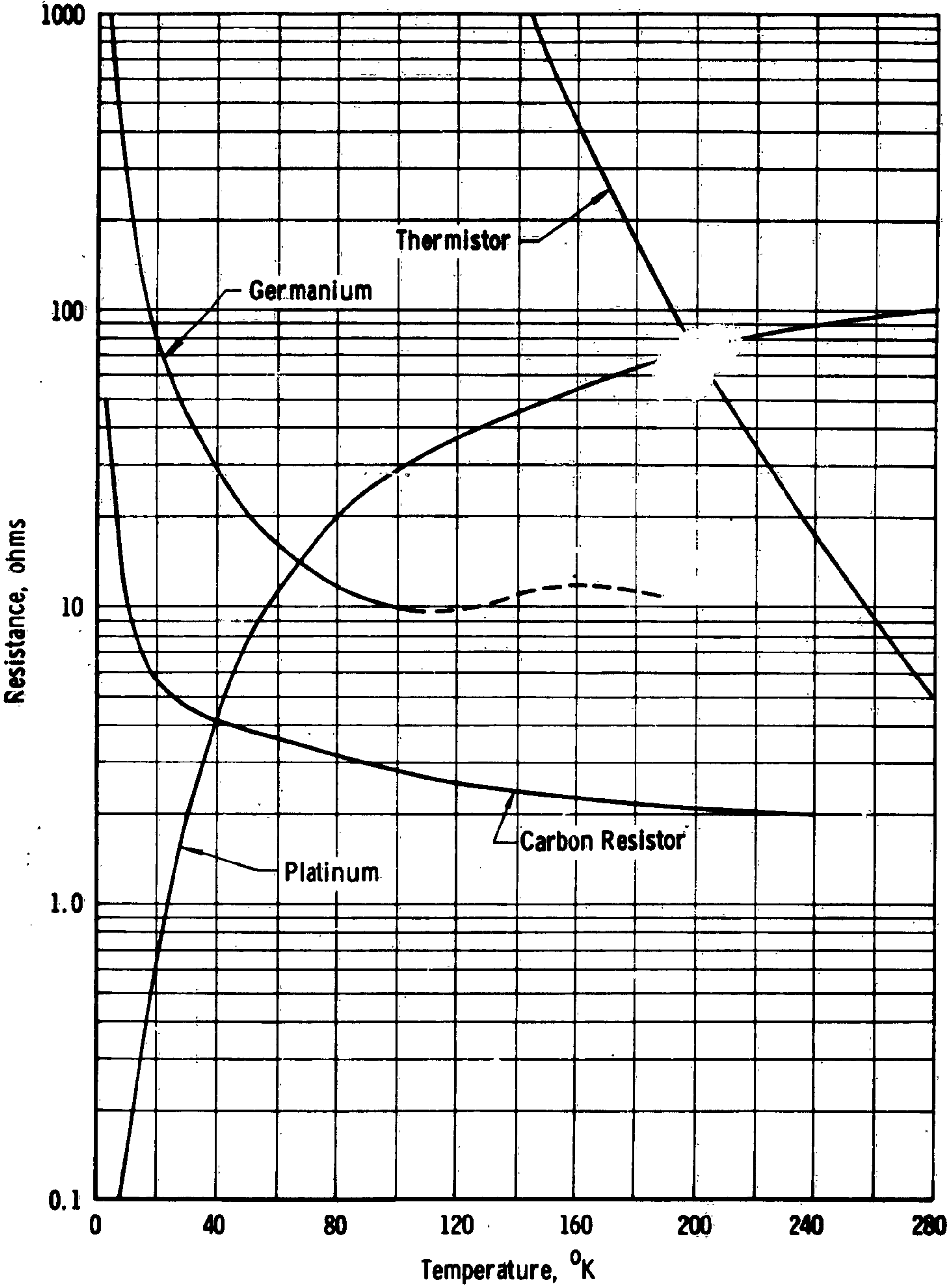


Fig. 20 Typical Temperature-Resistance Characteristics

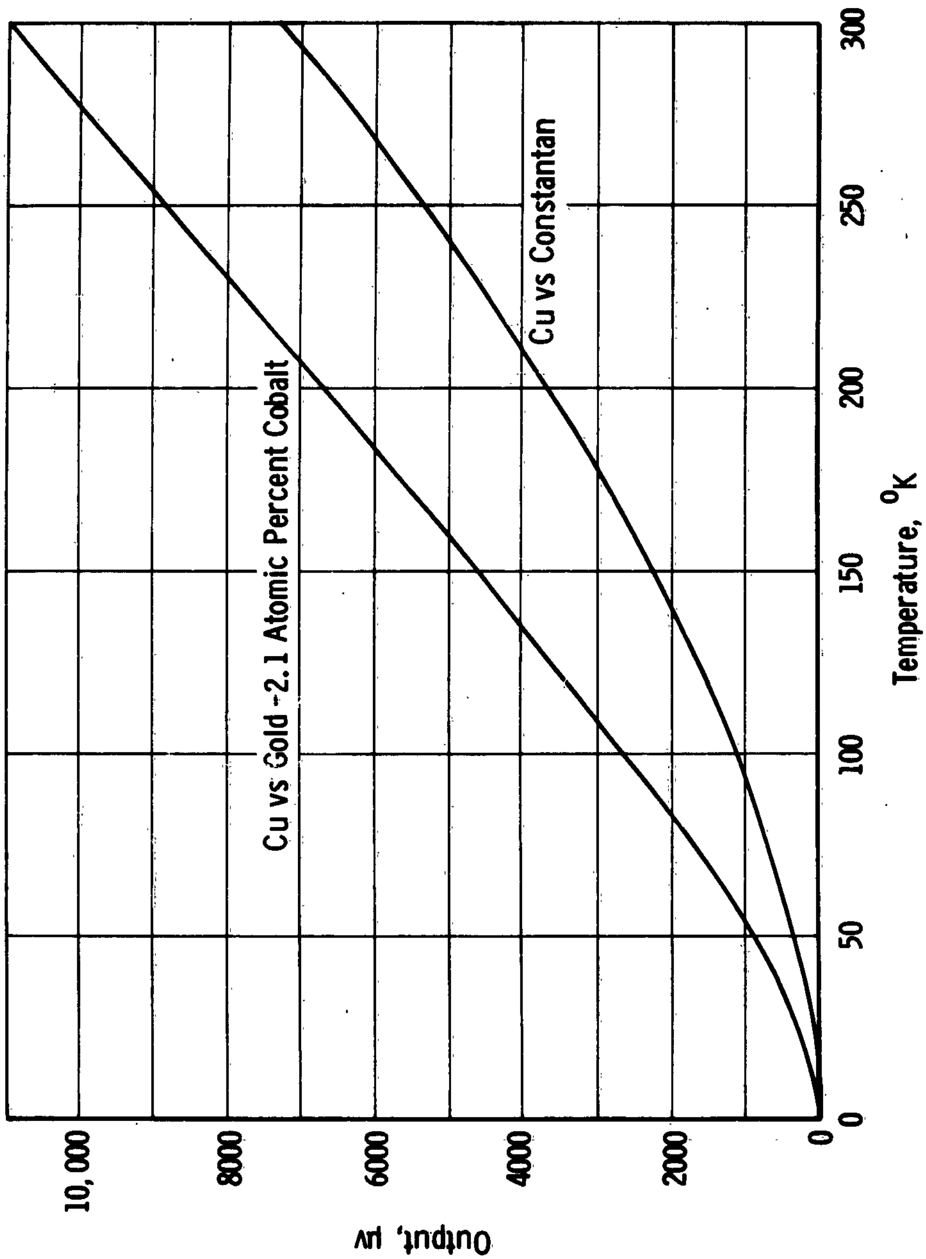


Fig. 21 Copper vs Gold-Cobalt and Constantan Thermocouples

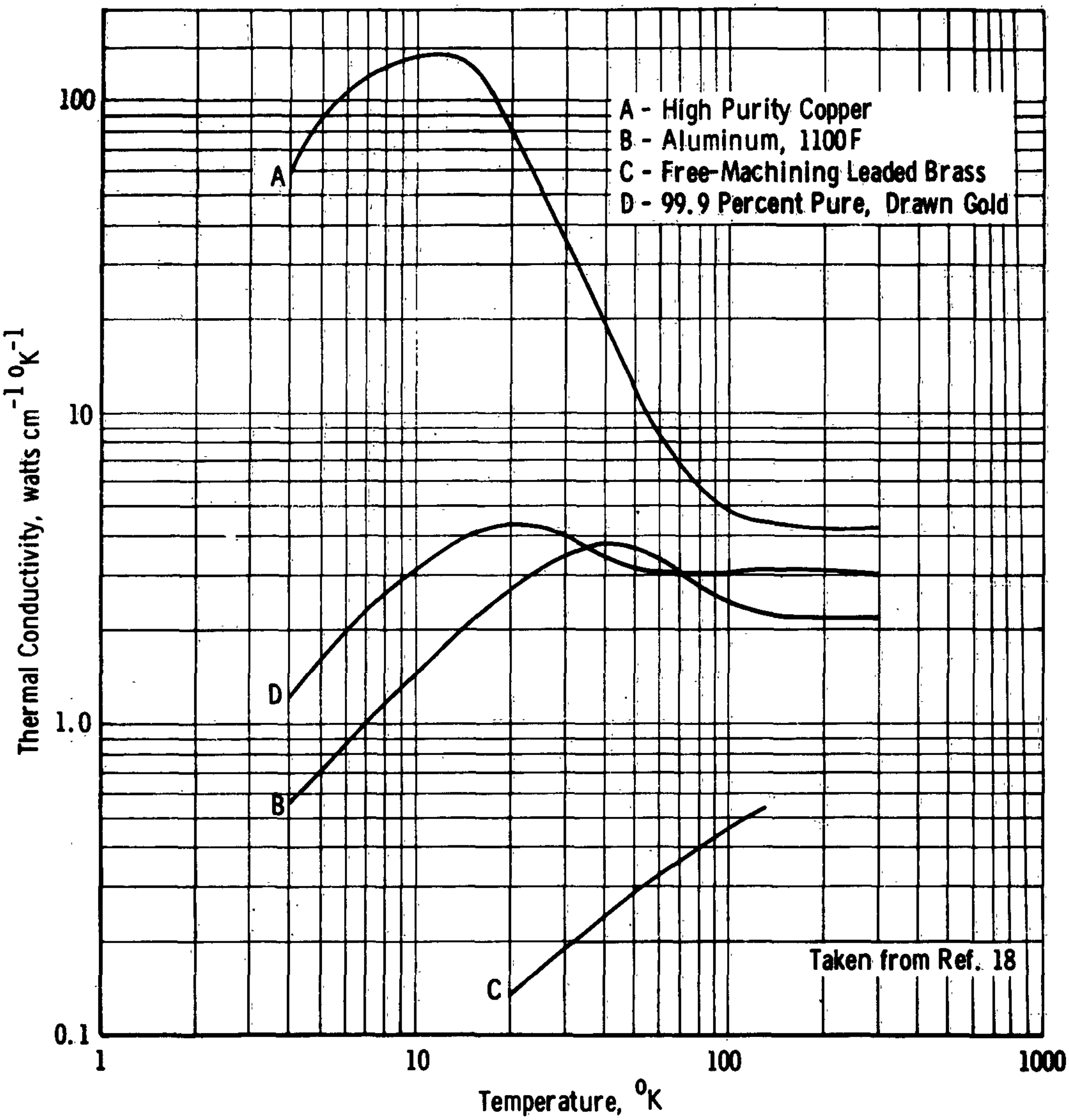


Fig. 22 Low-Temperature Thermal Conductivities

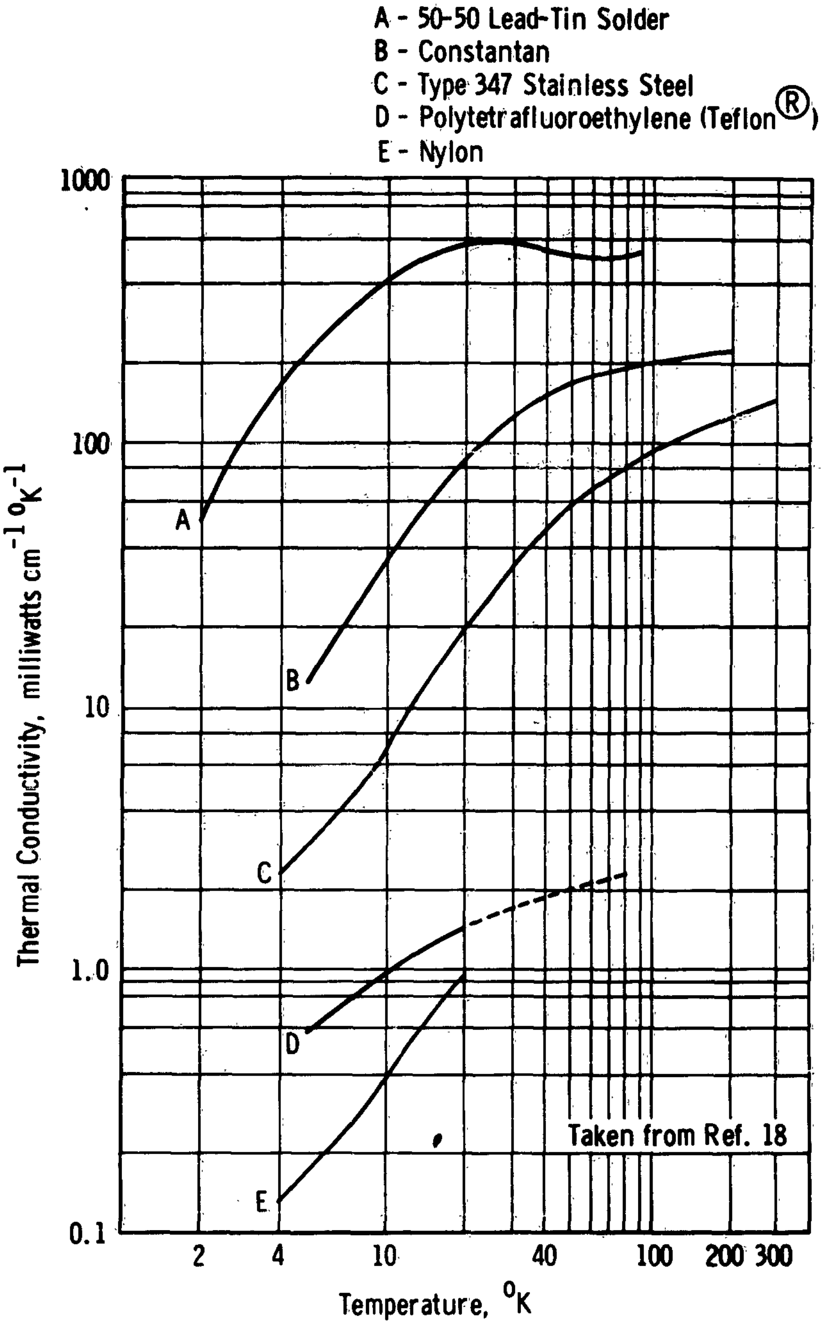


Fig. 23 Low-Temperature Thermal Conductivities

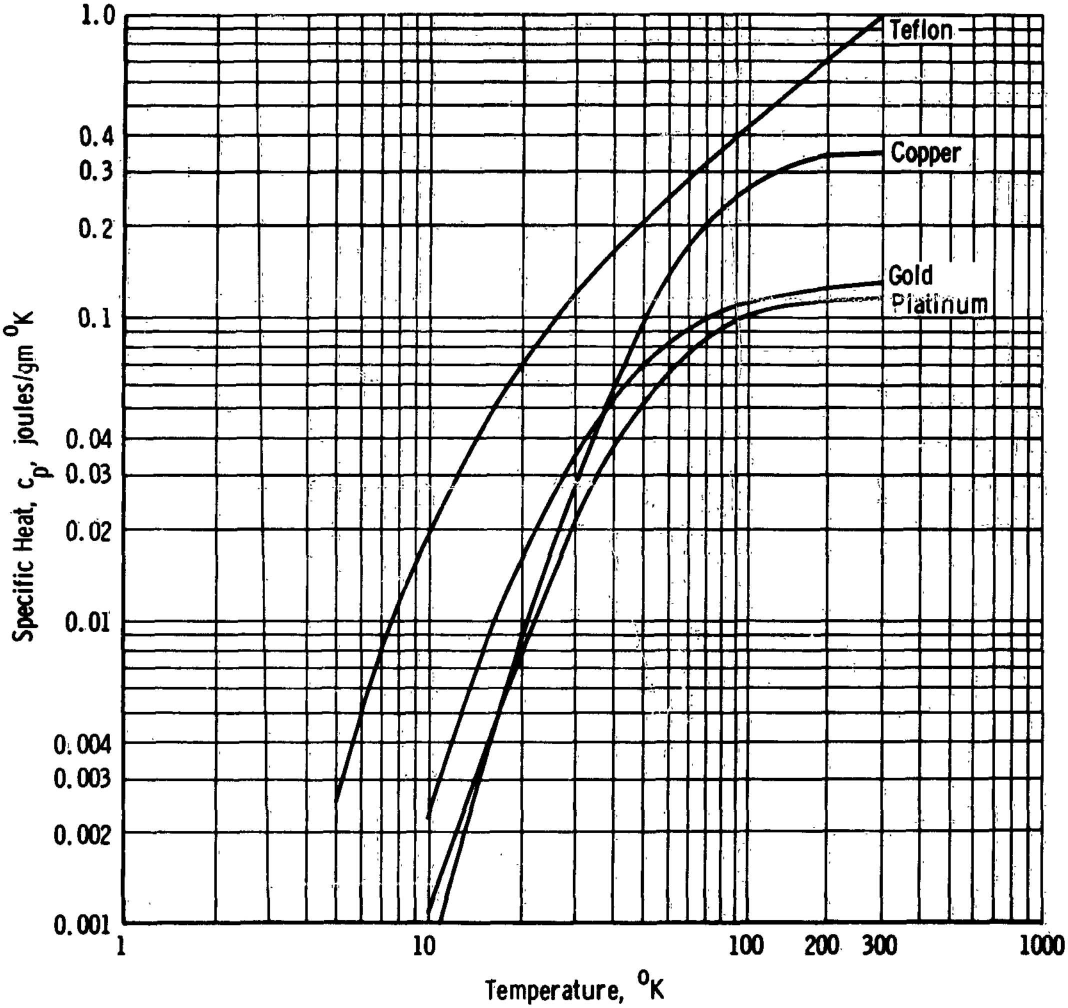


Fig. 24 Specific Heat vs Temperature

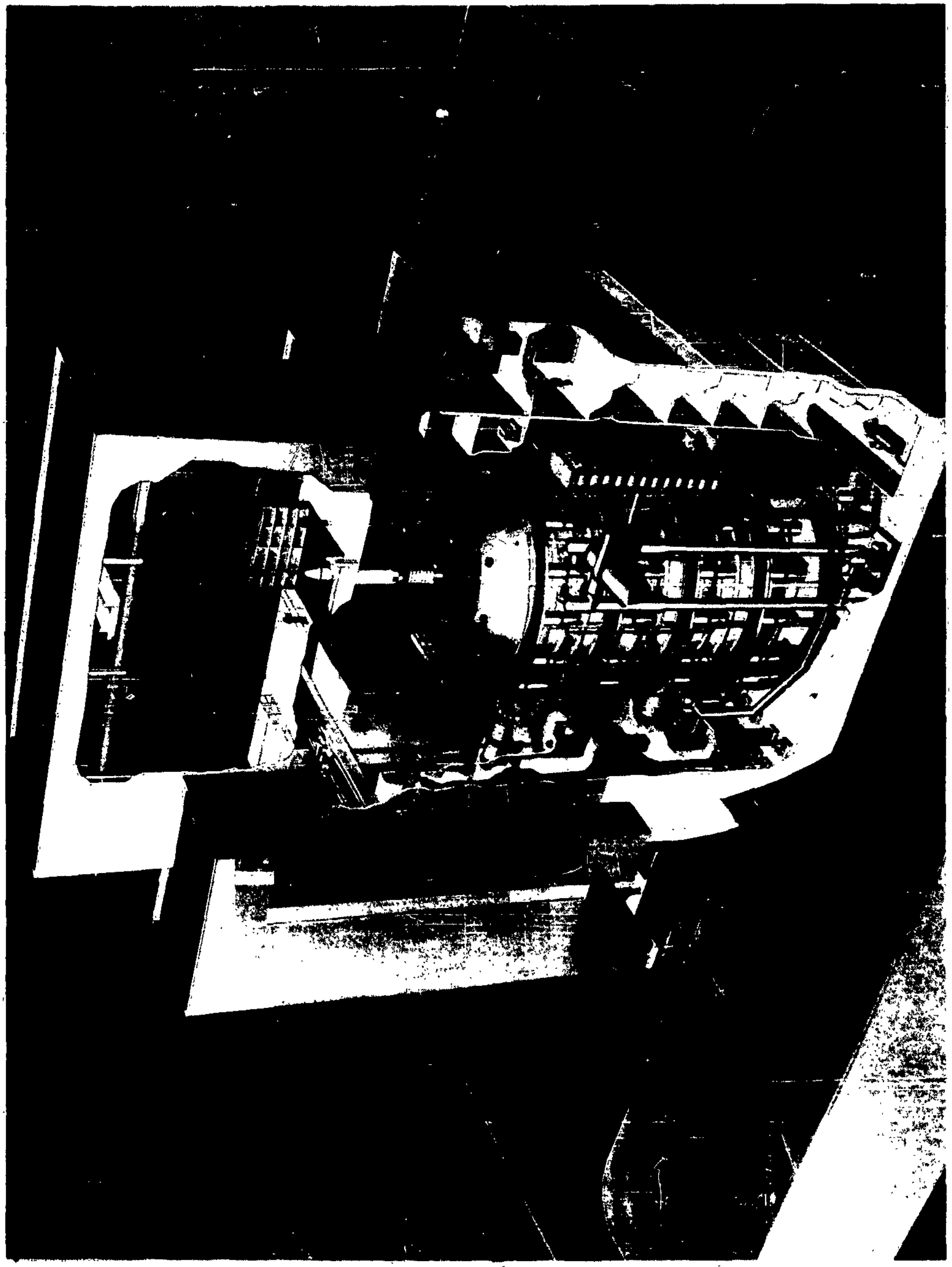
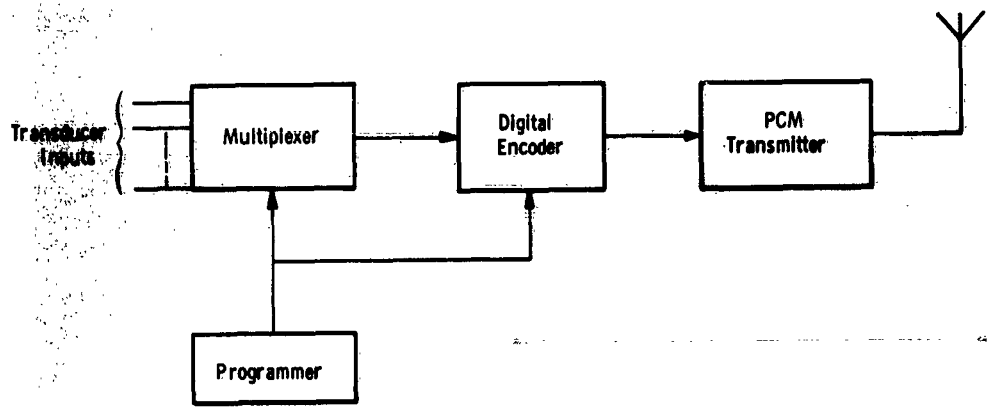
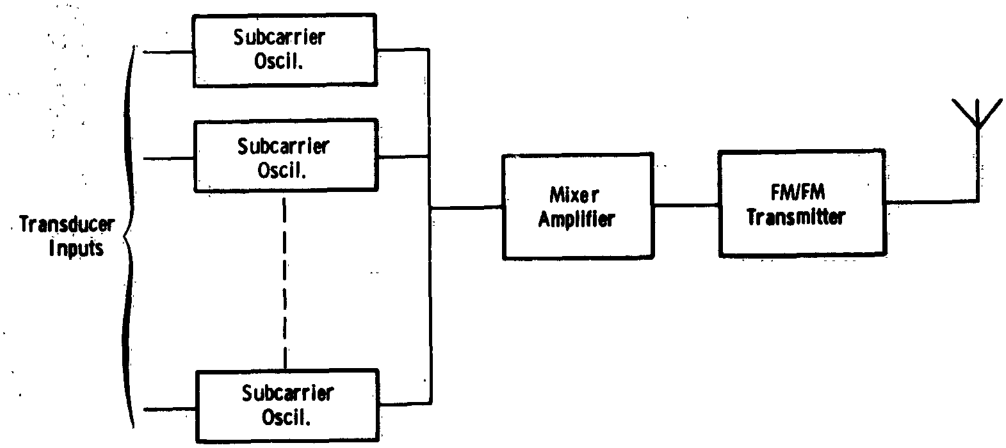


Fig. 25 Aerospace Systems Environmental Chamber, Mark I



PCM DATA LINK



FM/FM DATA LINK (Typical of 2)

Fig. 26 In-Chamber Data Acquisition Equipment, Aerospace Systems Environmental Chamber, Mark I

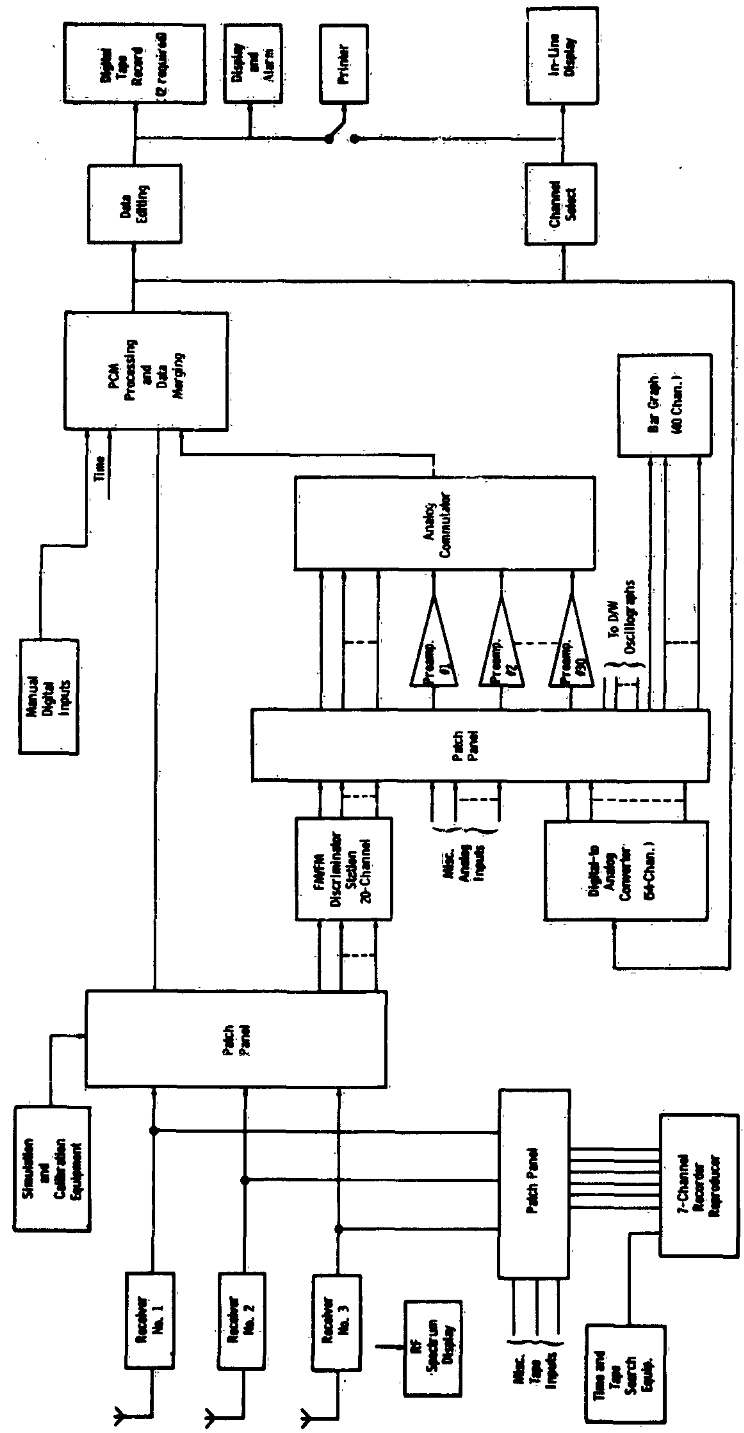


Fig. 27 Telemetry Reception and Data-Processing System, Aerospace Systems Environmental Chamber, Mark I

Arnold Engineering Development Center
Arnold Air Force Station, Tennessee
Rpt. No. AEDC-TDR-63-113. SPACE SIMULATION CHAMBER INSTRUMENTATION. June 1963, 72 p. incl 22 refs., illus.

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1. Space environmental conditions
2. Simulation
3. Test facilities
4. Instrumentation
5. Meters
6. Low temperature research

I. AFSC Program Area 040A
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